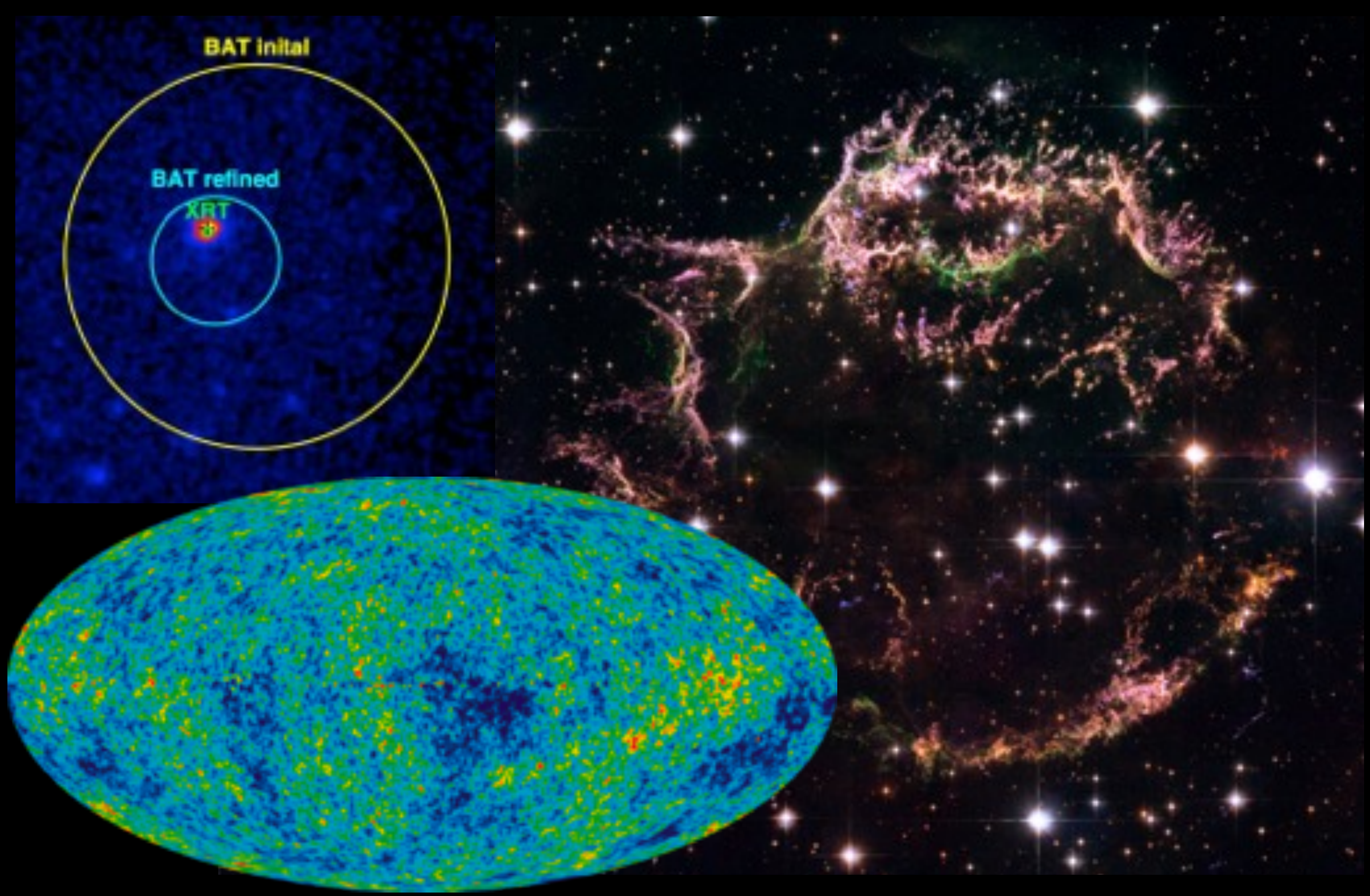
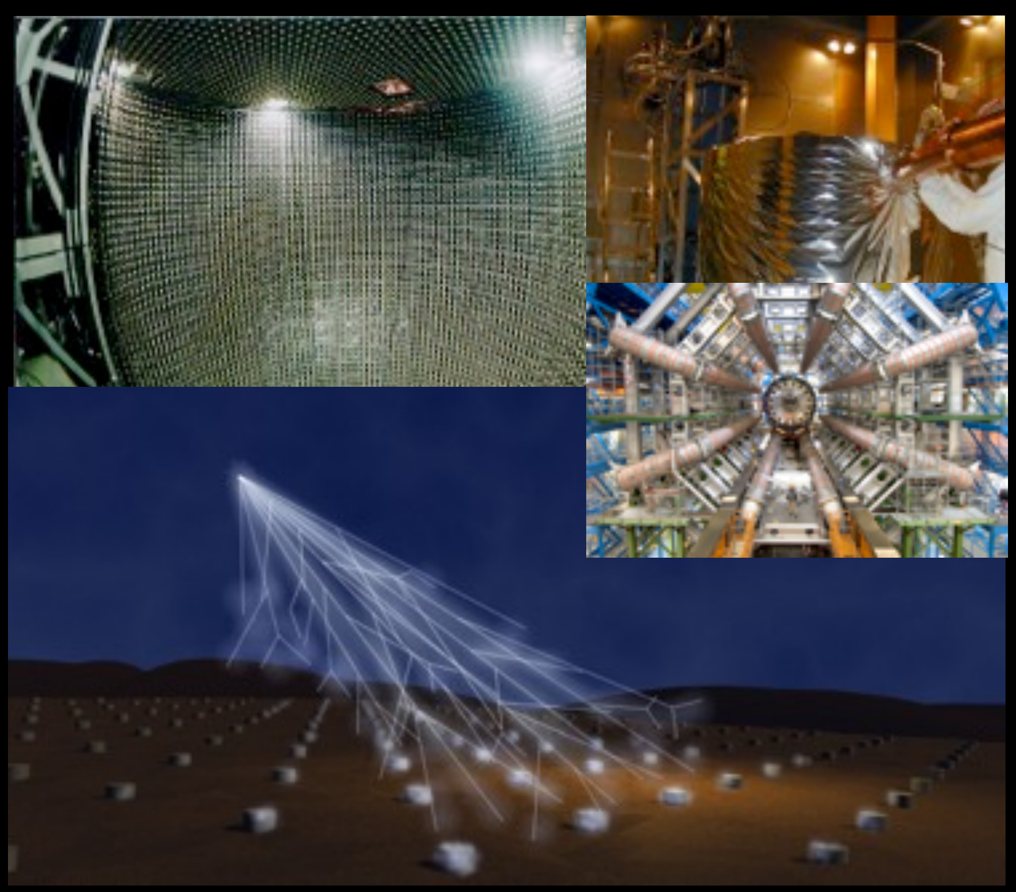
Gravitational Waves: A New Frontier in 21st Century Astrophysics

Duncan Brown,
Syracuse University
and the LIGO Scientific Collaboration

Our knowledge of the Universe comes from observing electromagnetic waves and from the detection and study of elementary particles



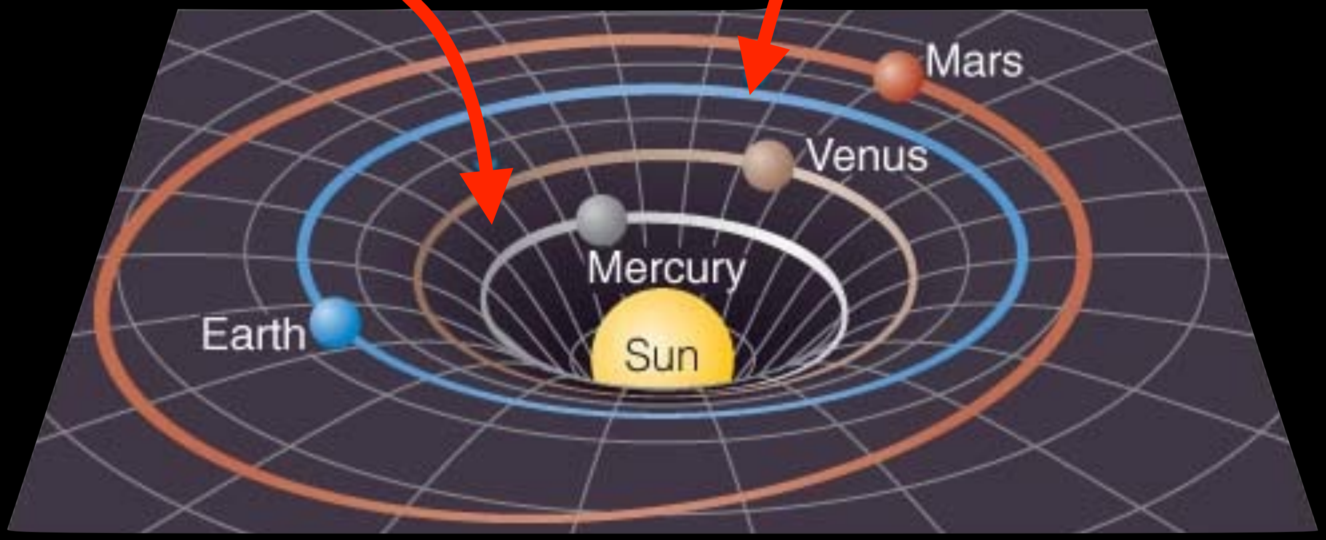


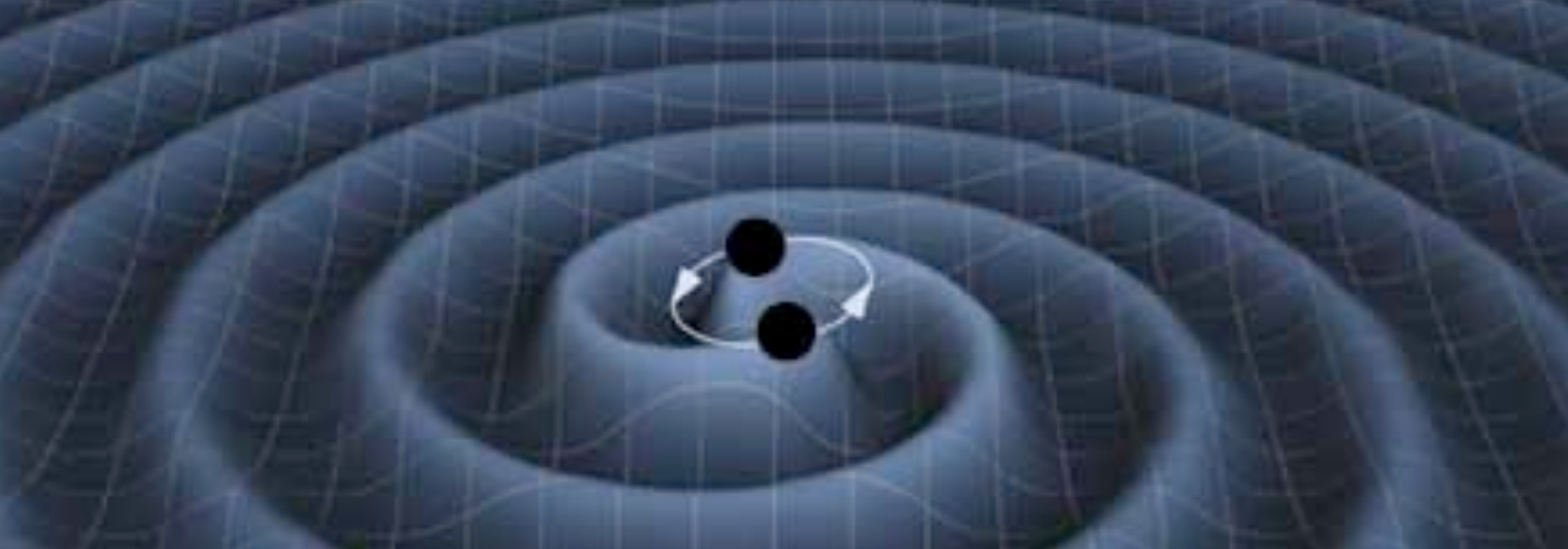
Gravitational Waves

- In General Relativity matter tells space how to curve and space tells matter how to move

The mass of the Sun curves the space around it

The planets follow the shortest path in the curved space

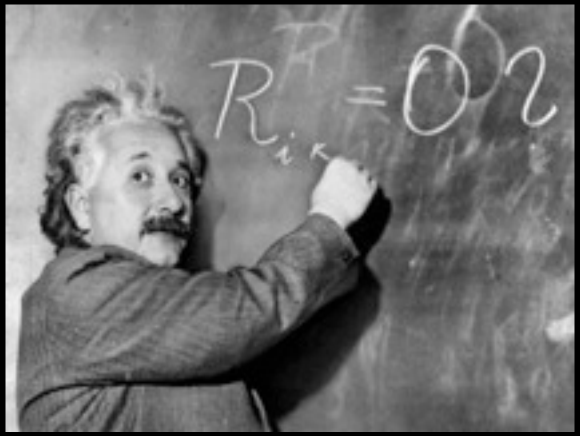




- When massive objects move around, the curvature of space changes
- Information about this change travels out at the speed of light as ripples in spacetime
- We call these ripples gravitational waves

- Gravitational waves are not just a different wavelength, they are a different spectrum
- Gravitational waves contain information about the sources that generated them
- Their detection would give us insight into fundamental physics and astronomy

Fundamental questions that gravitational-wave observations can answer



Is general relativity the correct theory of gravity?

What is the nature of one of the four fundamental forces?

What happens when two black holes collide?

Do black holes really have no hair?

What are the progenitors of short gamma ray bursts?

What is the engine that powers them?

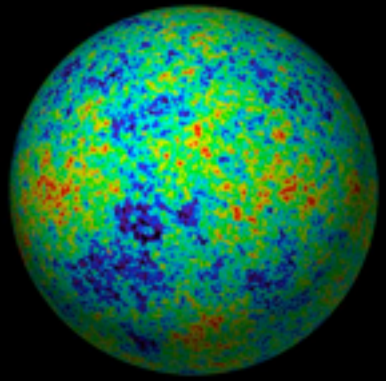
Fundamental questions that gravitational-wave observations can answer

How does core collapse power a supernova?

Is there a mass gap between neutron stars and black holes?

What is the maximum mass of a neutron star?

What is the nuclear equation of state at very high densities?



What new physics lies beyond the microwave background?

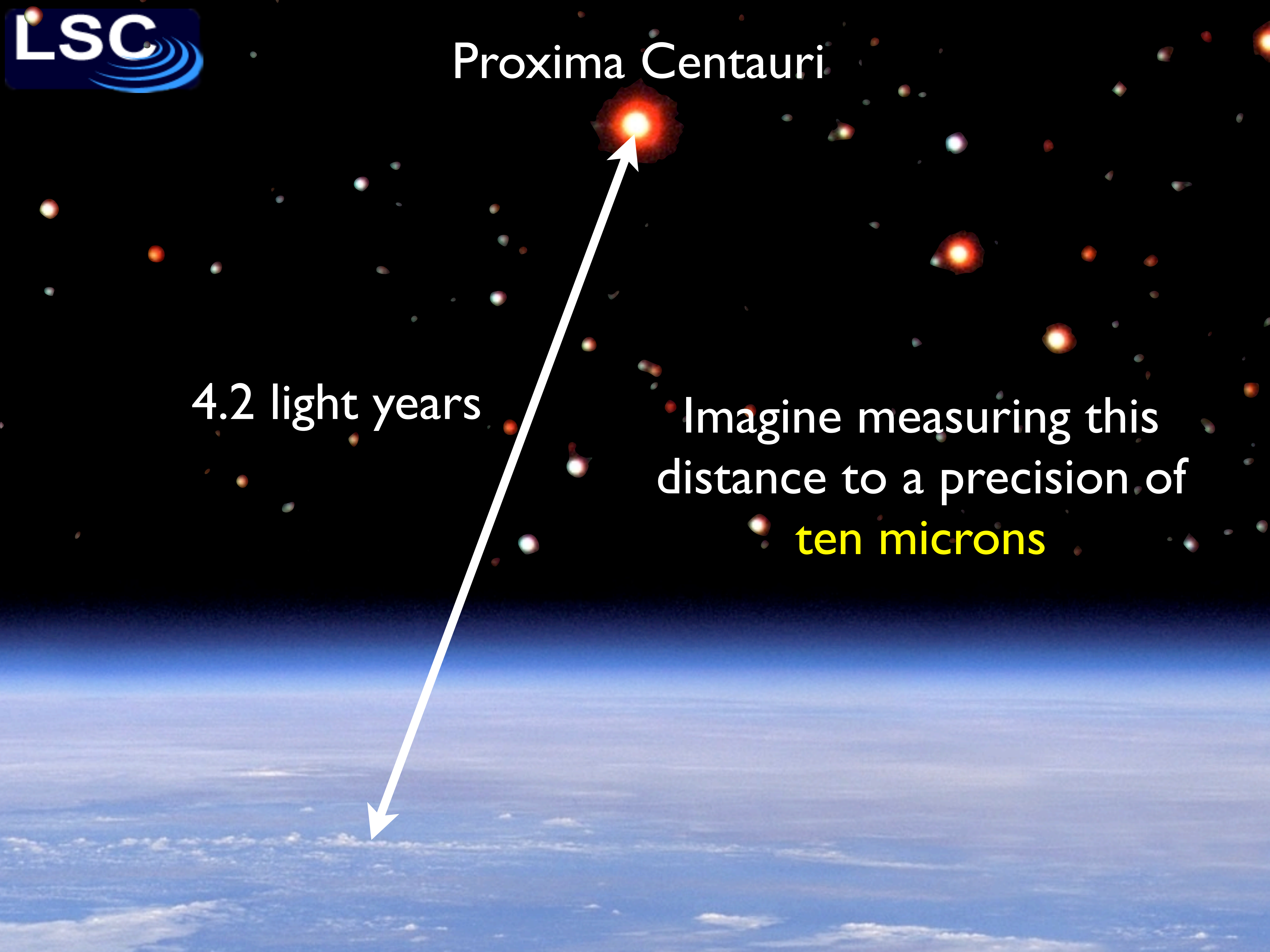
What happened in the earliest moments of creation?

- Gravitational wave stretch and squeeze the distance between freely falling objects

- The strength of a gravitational wave is given by the strain h(t) = change in length / length

- Typical strains on Earth for astrophysical sources are

$$h \sim \frac{G}{c^4}\frac{E_{\mathrm{NS}}}{r} \sim 10^{-21}$$

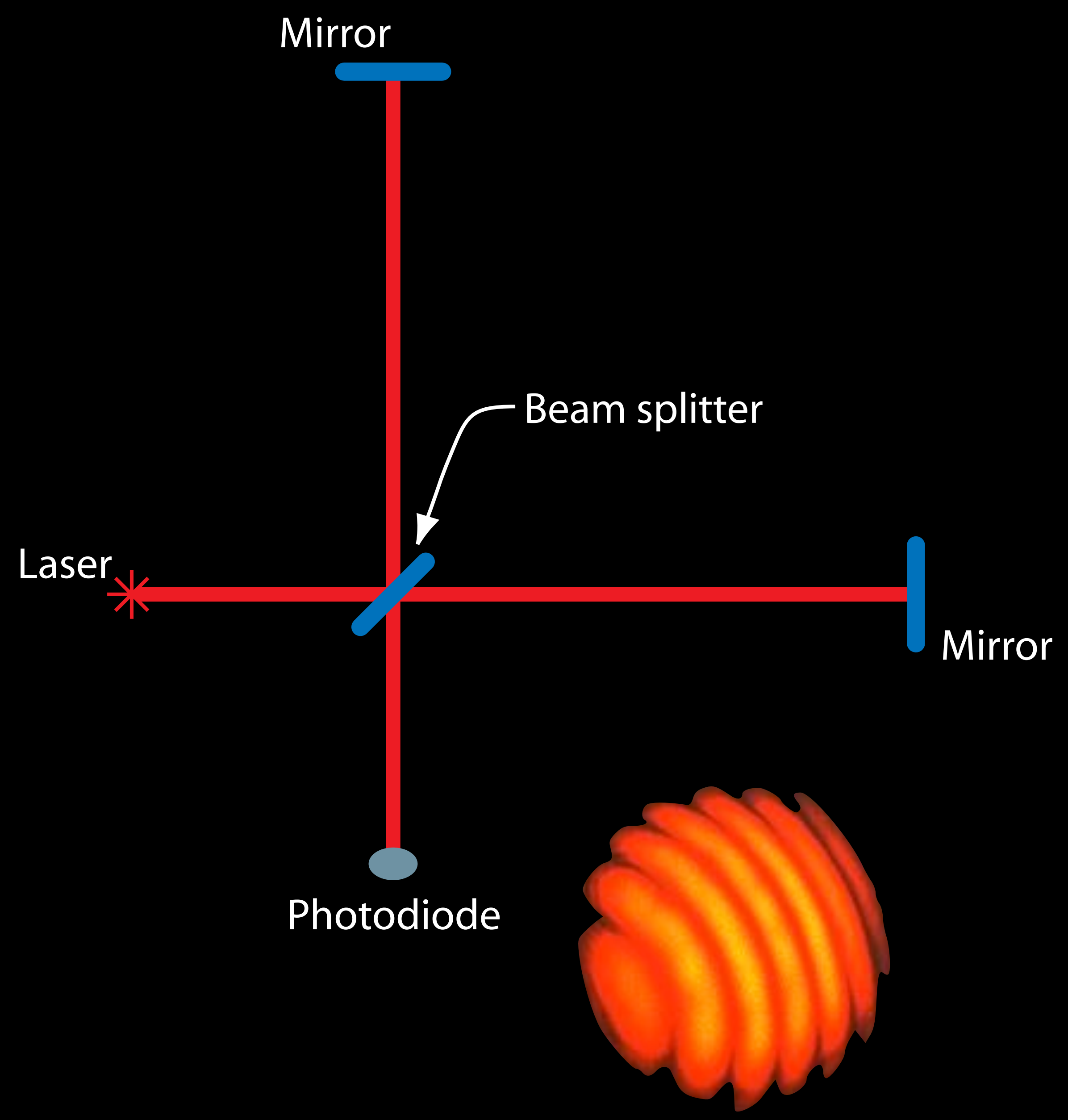

LSC
Proxima Centauri
4.2 light years
Imagine measuring this distance to a precision of ten microns

- The radiated energy is enormous

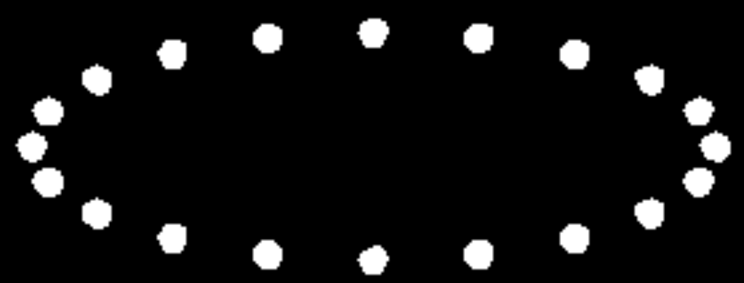
$$L_{\mathrm{GW}} \sim \left(\frac{c^5}{G}\right)\left(\frac{v}{c}\right)^6\left(\frac{R_{\mathrm{S}}}{r}\right)^2 \sim 10^{59}\mathrm{erg/s}$$

- c.f.
    - Solar luminosity L ~ 10^{33} erg/s
    - Gamma Ray Bursts L ~ 10^{49-52} erg/s

Laser Interferometers

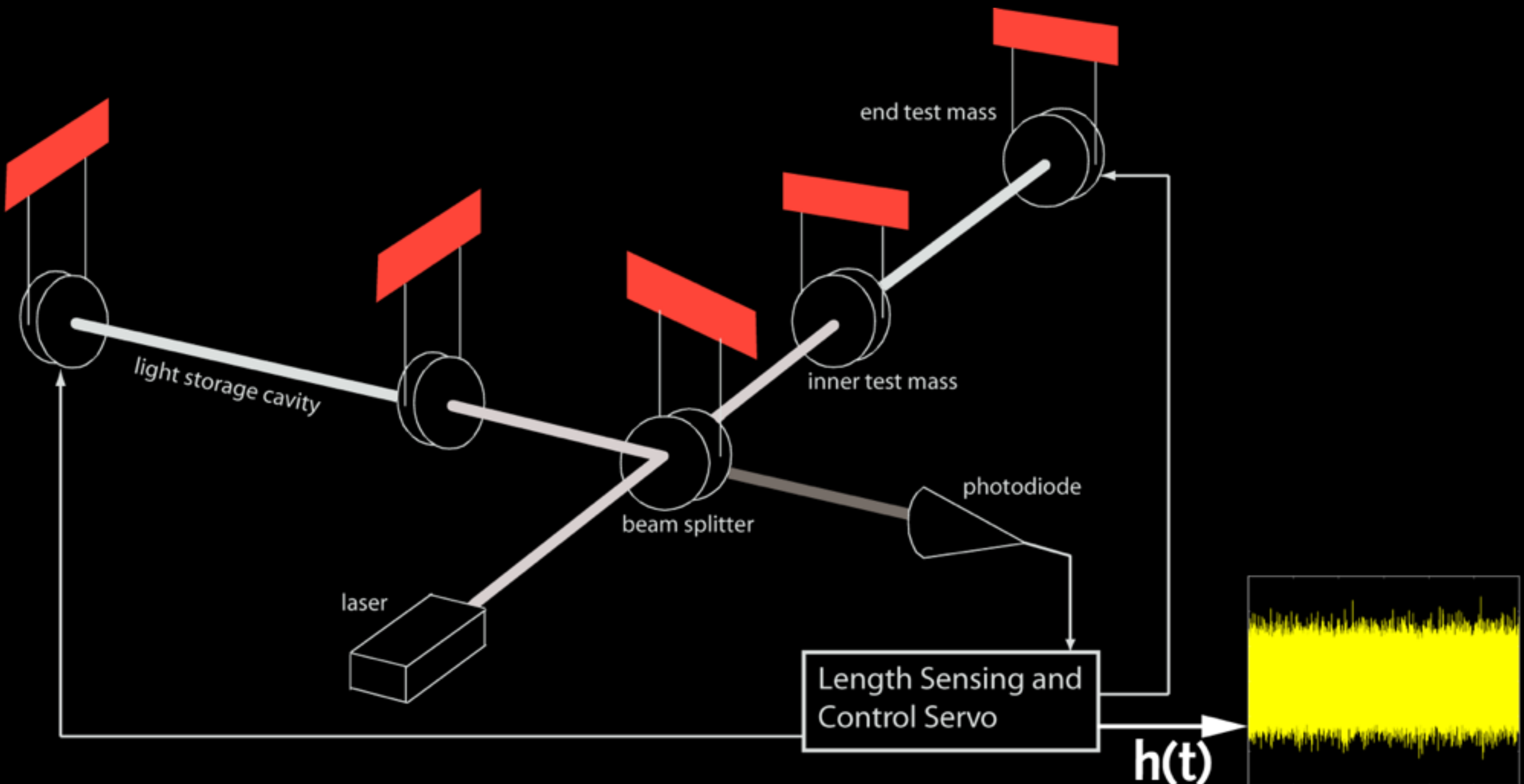


Michelson interferometer



Gravitational waves stretch and squeeze the detector's arms

The Laser Interferometer Gravitational-wave Observatory: LIGO

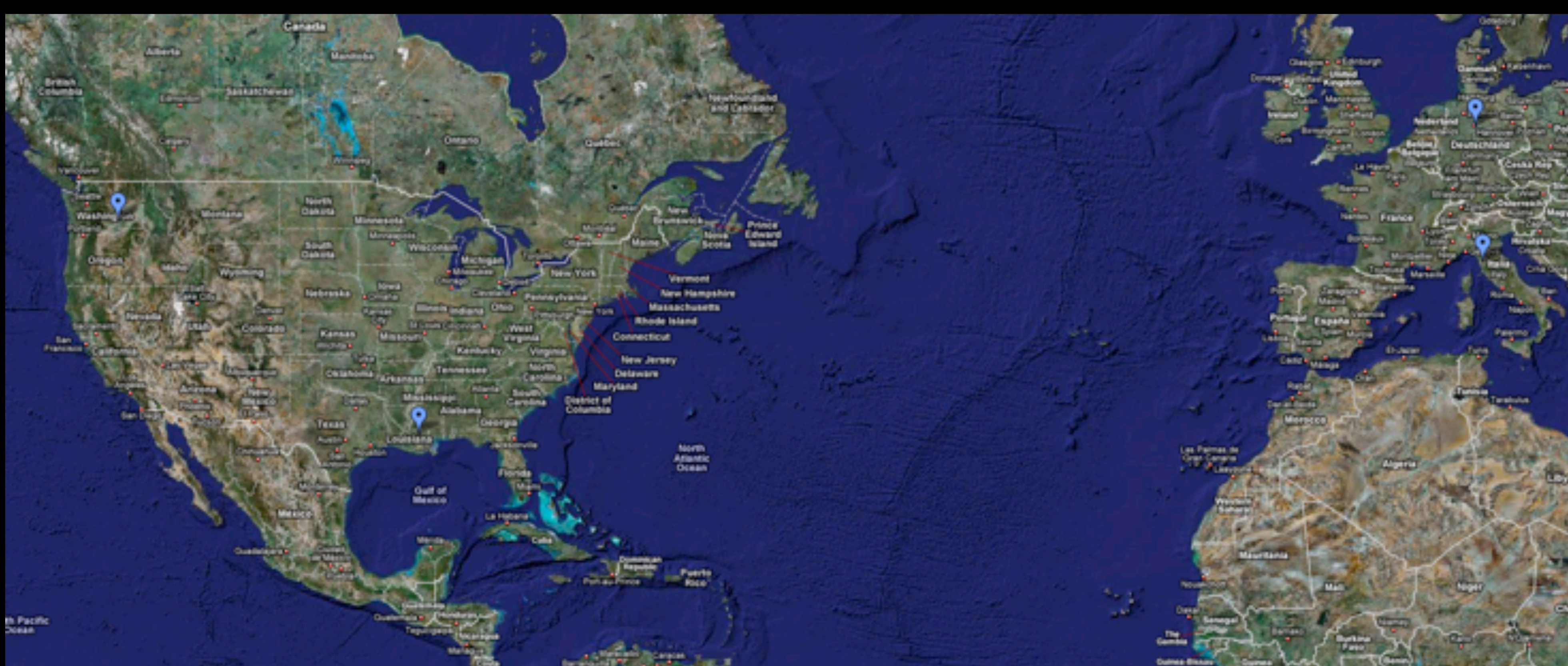


Abbott,..., DAB, et al, Rep. Prog. Phys. 72, 076901 (2009)

LIGO Livingston Observatory

LIGO Hanford Observatory

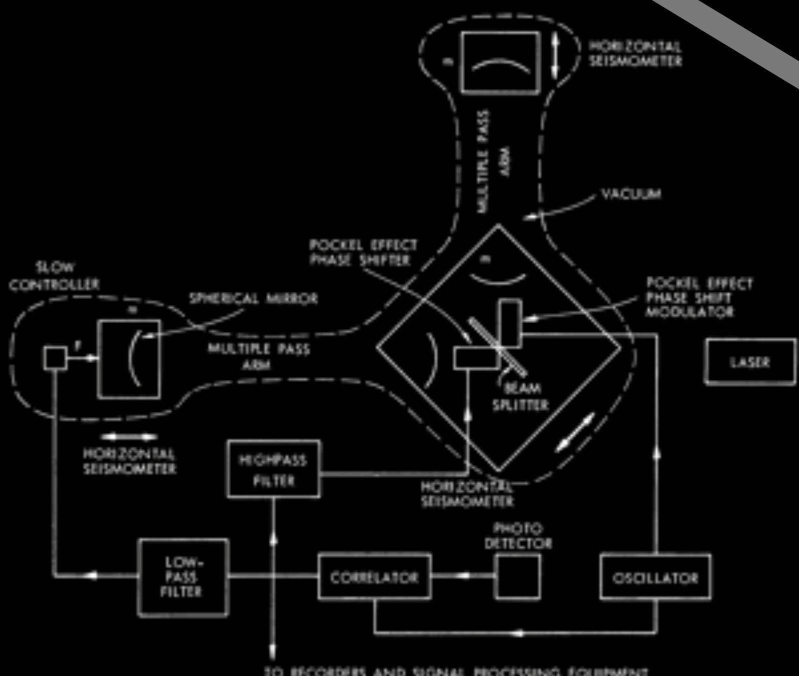
Virgo
Near Pisa, Italy



Three detectors on two continents

Decades of work in gravitational-wave detector science is about to pay off

1972



Weiss' design for a first-generation gravitational-wave interferometer: LIGO

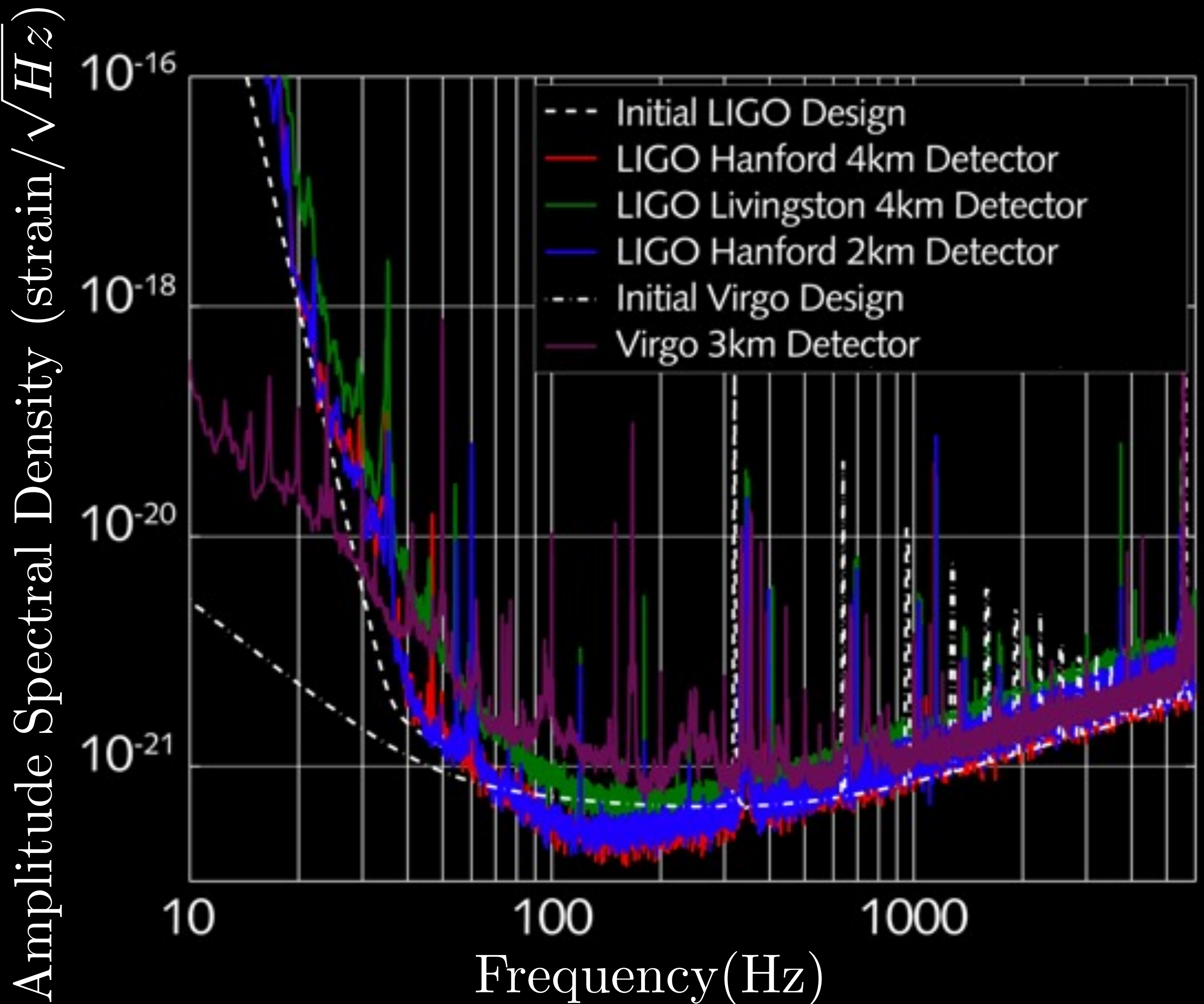
Construction of LIGO facilities

1994

2005

Initial LIGO reaches design sensitivity

Opening a new field of physics



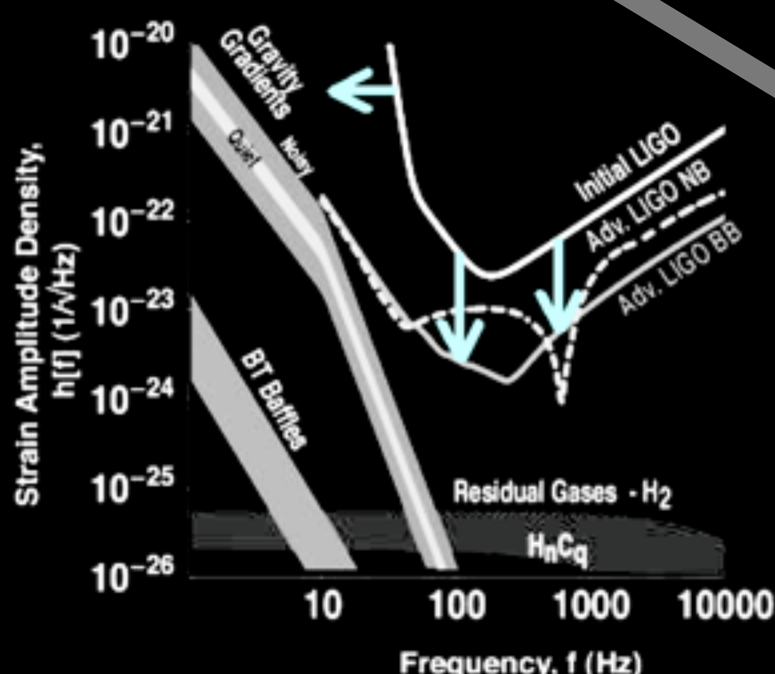
Initial LIGO demonstrated that we can measure displacements of 10^{-19} m

"Scientists now have ground-based interferometric detectors that are on a path to reaching the sensitivity at which the detection of gravitational waves is virtually assured."

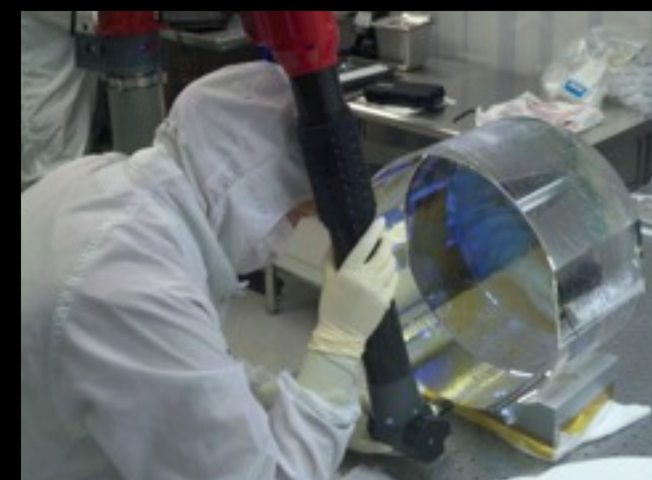
National Academy of Sciences 2010 Decadal Survey of Astronomy and Astrophysics

Advanced LIGO will detect gravitational waves from astrophysical sources

1996



Planning of second-generation detectors begins: Advanced LIGO

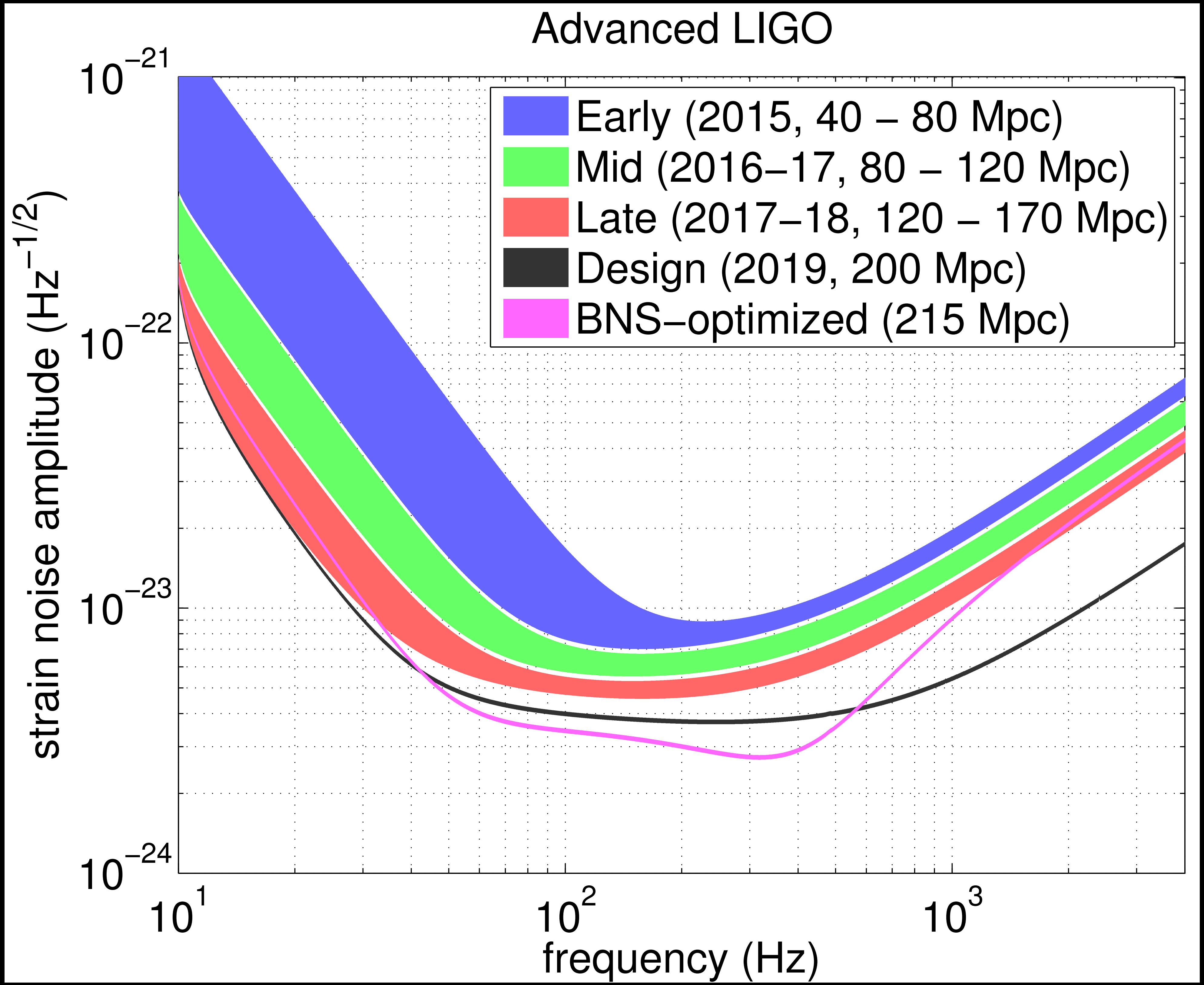


Advanced LIGO funded: construction begins

2008

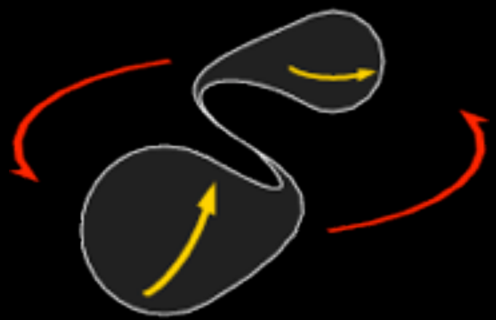
2015

Advanced LIGO begins observations of the gravitational-wave sky

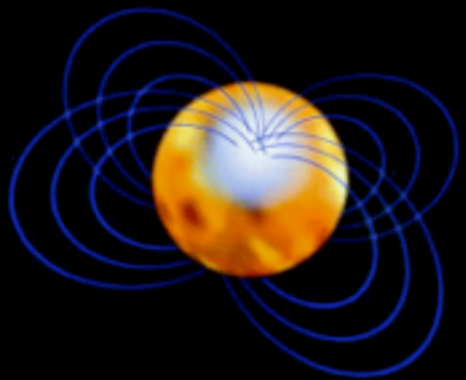


Aasi, ..., DAB, et al. (LSC and Virgo) arXiv:1304.0607

Sources of Gravitational Waves

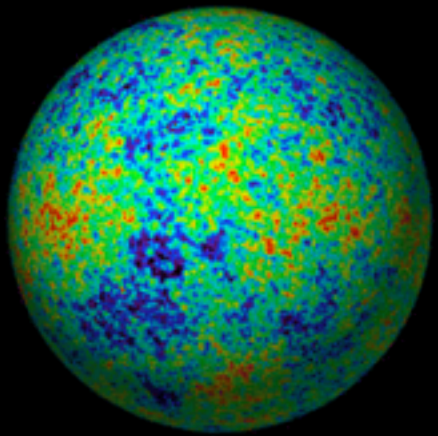


Compact binary coalescence (CBC): inspiral, merger and ringdown of black holes and neutron stars



Continuous Sources: spinning neutron stars

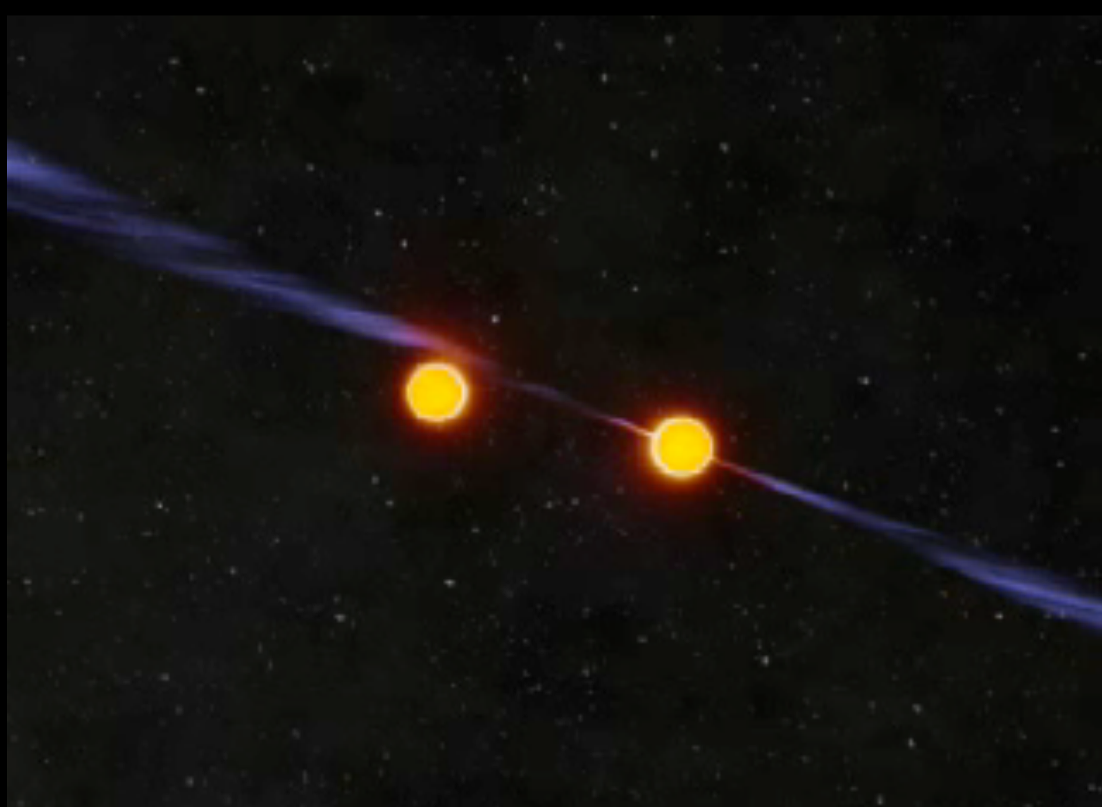
Short bursts: supernovae, unmodeled transient sources



Stochastic sources: gravitational wave background from the big bang

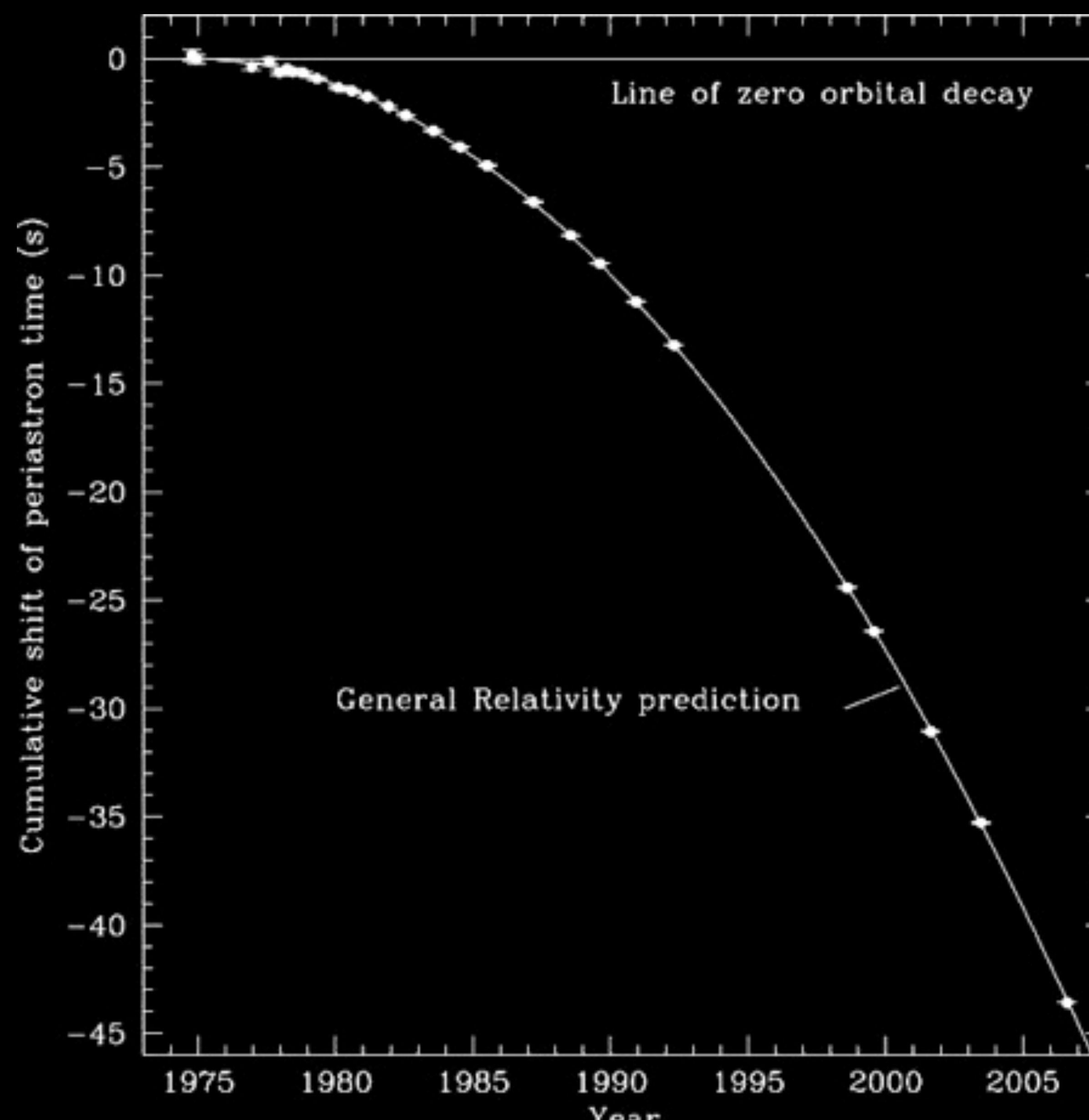
Binary Pulsars

Radio detections of 10 binary pulsars in our galaxy



John Rowe Animation

Radio observations of binary pulsars confirm that energy loss is consistent with gravitational waves



Weisberg, Nice, Taylor ApJ **722** 1030 (2010)

- LIGO's most likely source is Binary Neutron Stars: BNS rate is 0.4 - 400 yr^{-1}

- Two observations of x-ray binaries that will likely evolve to Binary Black Holes (IC10-X1, NGC300-X1)

- LIGO Binary Black Hole rate 0.4 - 1000 yr^{-1}

- Neutron star-black hole rate 0.2 - 300 yr^{-1}

Abadie, ..., DAB, et al. (LSC and Virgo) Class Quant Grav **27** 173001 (2010)

Binary Coalescence

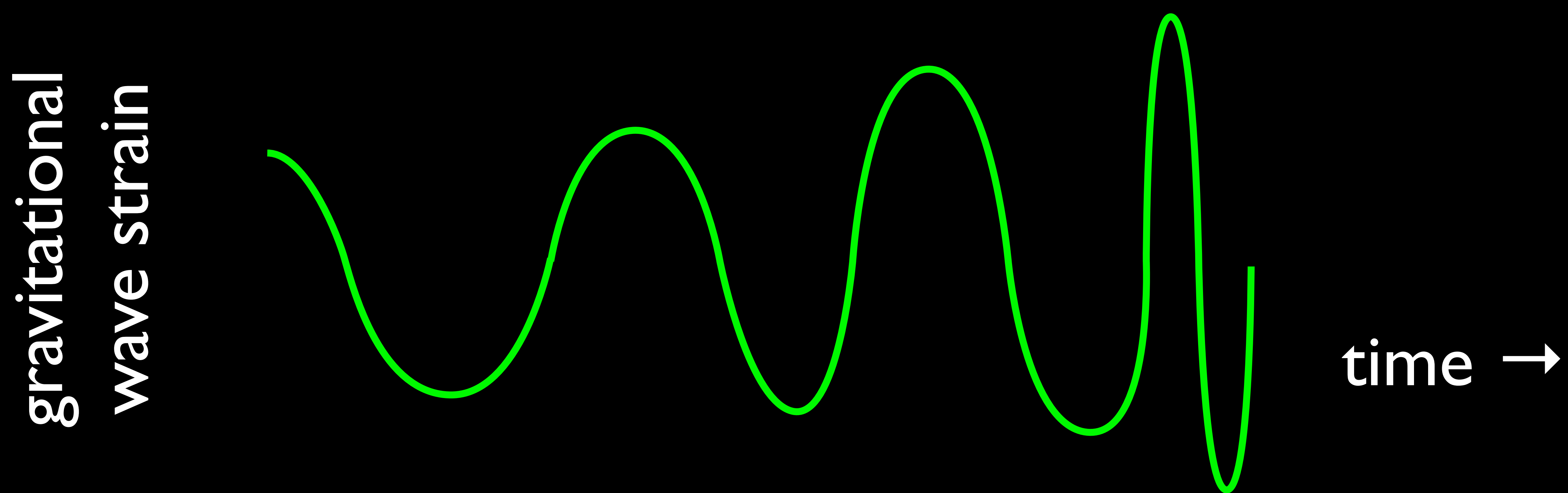
$$E = -\frac{1}{2}\frac{G\mu M}{r} \qquad \mathcal{F} = -\frac{32}{5}\frac{G^4}{c^5}\frac{M^3\mu^2}{r^5}$$

$$\frac{dr}{dt} = -\mathcal{F}\Big/\frac{dE}{dr} = -\frac{64}{5}\frac{G^3}{c^5}\frac{M^2\mu}{r^3}$$

Peters and Mathews Phys Rev **131** 435 (1963)

Binary Coalescence

$$r(t) = \left(\frac{256}{5}\frac{G^3}{c^5}M^2\mu\right)^{\frac{1}{4}}(t_c - t)^{\frac{1}{4}}$$



Peters and Mathews Phys Rev **131** 435 (1963)

Detecting Compact Binaries

- Waveforms “known” so use matched filtering

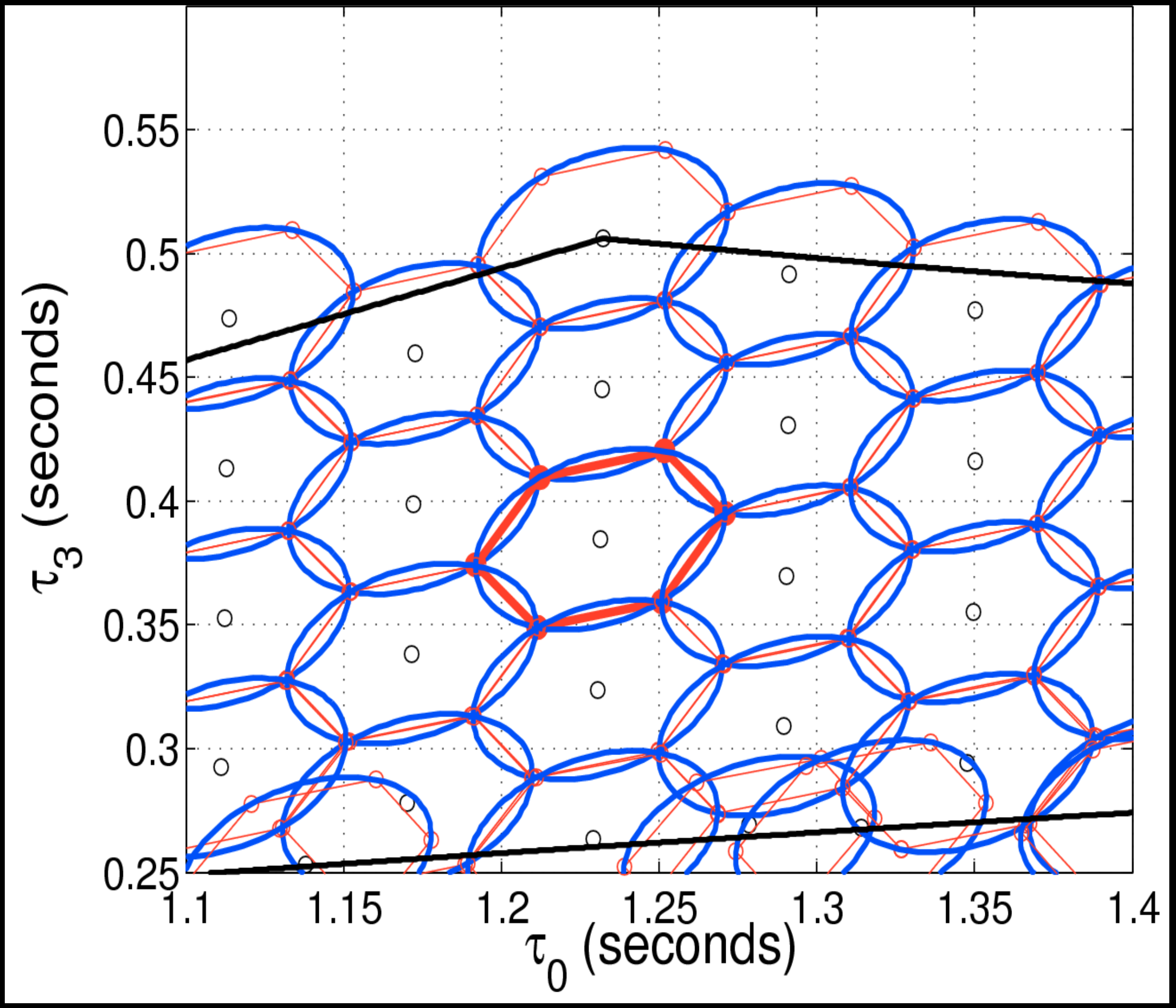
$$\rho = \frac{\langle s|h\rangle}{\sqrt{\langle h|h\rangle}} \qquad \langle a|b\rangle = 4\mathrm{Re}\int_{f_{\mathrm{low}}}^{f_{\mathrm{high}}} \frac{\tilde{a}(f)\tilde{b}(f)}{S_n(f)}\,df$$

- Detector data contains non-Gaussian transients which complicates search

Allen, Anderson, Brady, DAB, Creighton Phys Rev D **85** 122006 (2012)
Babak,..., DAB, et al. Phys Rev D **87** 024033 (2013)

Template bank

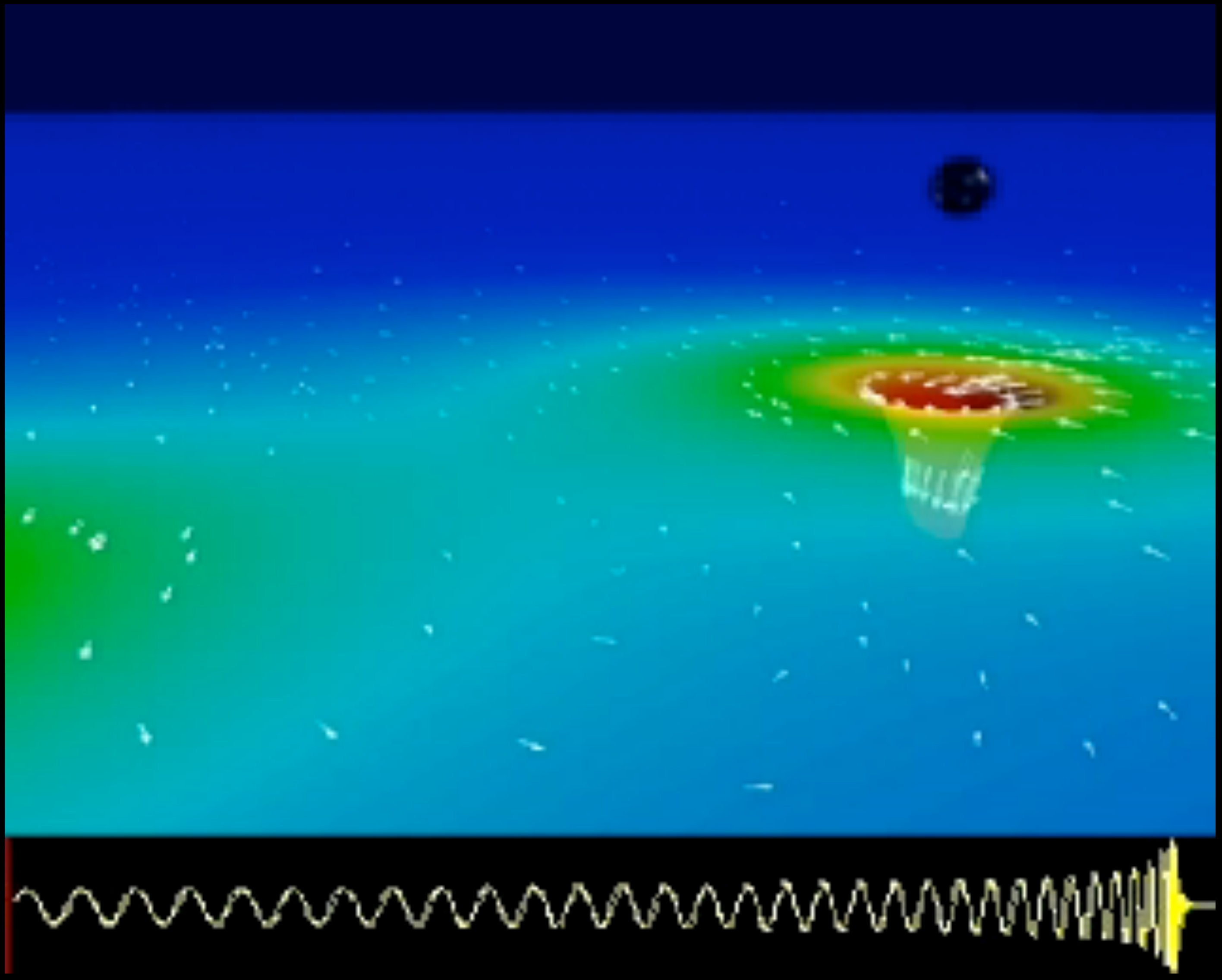
- Place a grid of waveforms so that no more than 3% of SNR is lost due to mismatch between signal and nearest template



Owen and Sathya PRD 60, 022002 (1999)
Babak et al. Class.Quant.Grav. 23 5477 (2006)
DAB, Harry, Lundgren, Nitz PRD **86** 084017 (2012)

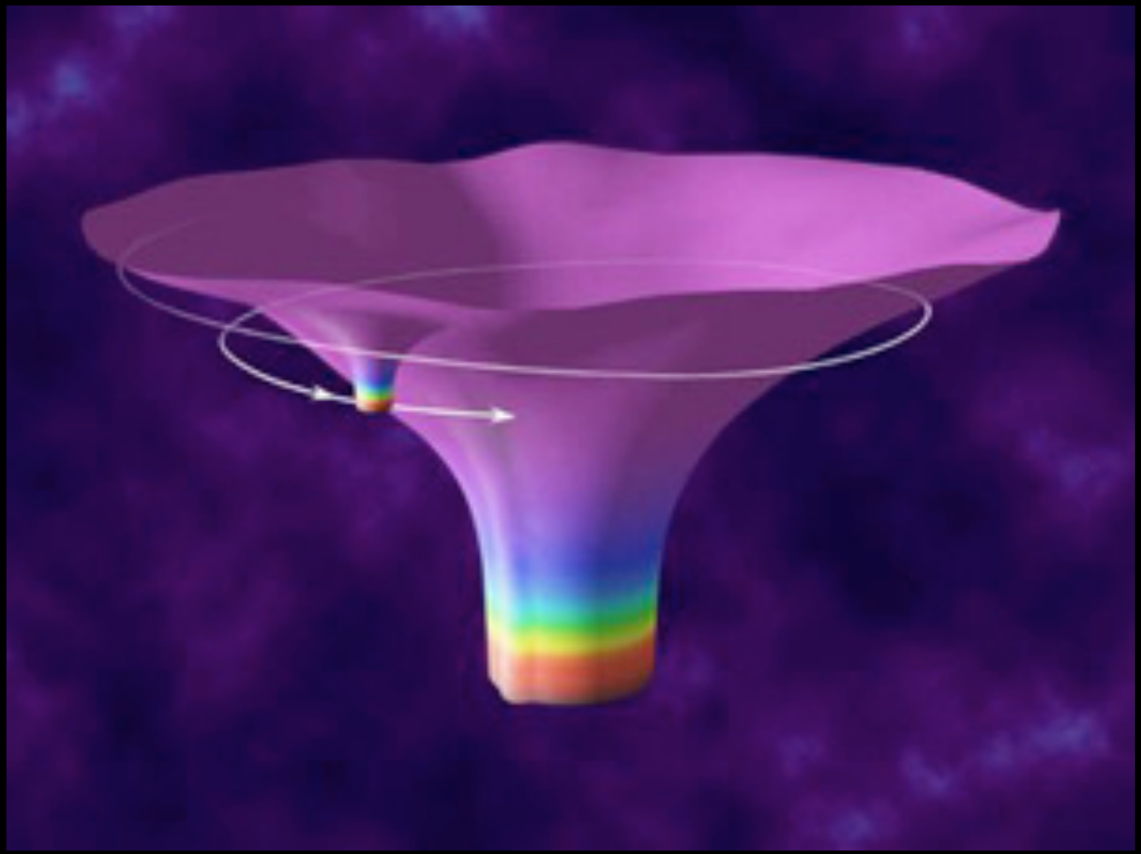
Simulating Extreme Spacetimes

At high masses, high mass ratios or if the black holes are spinning, the approximations used to model BNS break down: need full numerical solution of Einstein Equations



Boyle, DAB, Kidder, Mroue, Pfeiffer, Scheel, Teukolsky, PRD **76** 124038 (2007)
Scheel, Boyle, Chu, Kidder, Matthews, Pfeiffer PRD **79** 024003 (2009)

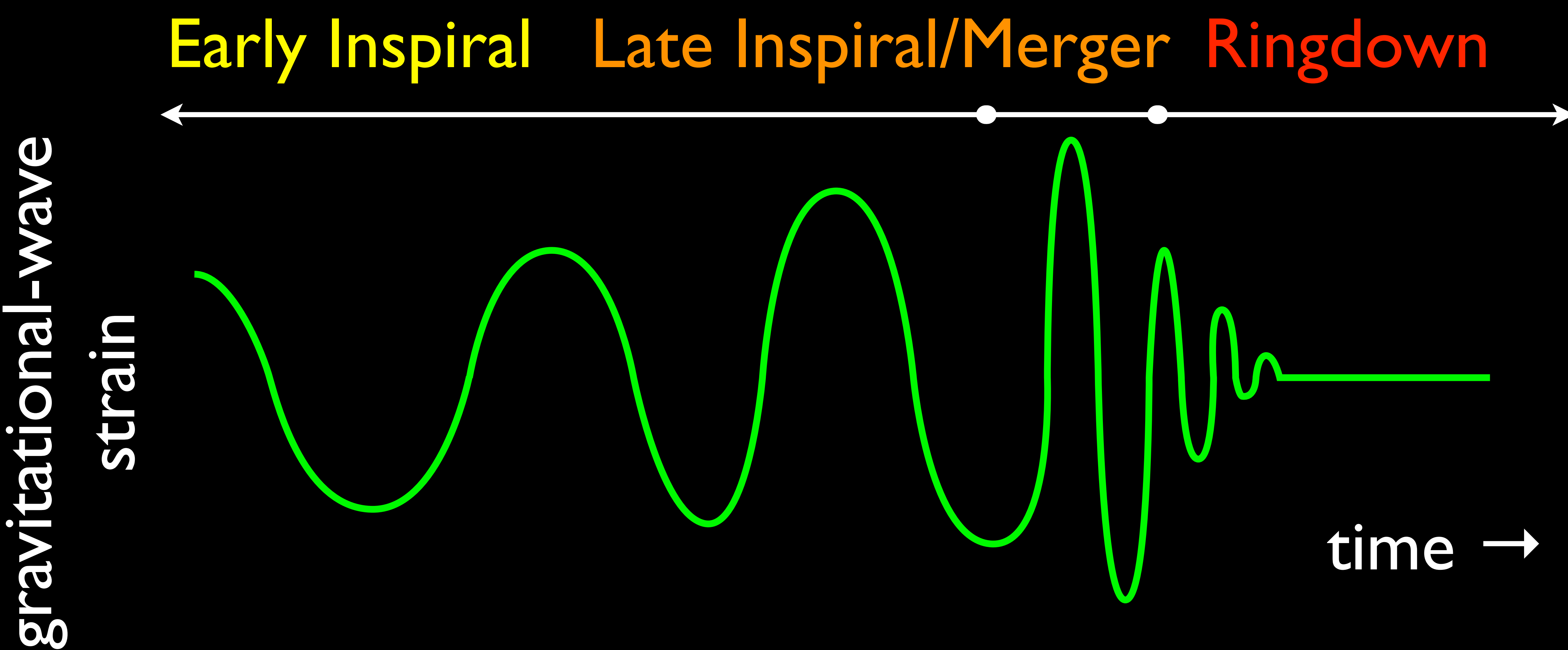
- Gravitational-wave detectors will explore the dynamics of orbits and mergers in the most strongly curved spacetimes



The inspiral of a neutron star into an intermediate mass black hole will probe the structure of the black holes' spacetime

DAB, Brink, Fang, Gair, Li, Lovelace, Mandel, Thorne PRL **99** 201102 (2007)
Mandel, DAB, Gair, Miller ApJ **681** 1431 (2008)

We can construct searches using waveforms modeled by a combination of post-Newtonian theory, numerical relativity and perturbation methods



Buonanno and Damour, PRD **59** 084006 (1999)
Pan et al. PRD **84** 124052 (2011)
Taracchini et al. PRD **86** 024011 (2012)
DAB, Kumar and Nitz PRD **87** 082004 (2013)
Kumar, MacDonald, DAB, Pfeiffer, Cannon et al. PRD **89** 042002 (2014)

Challenges

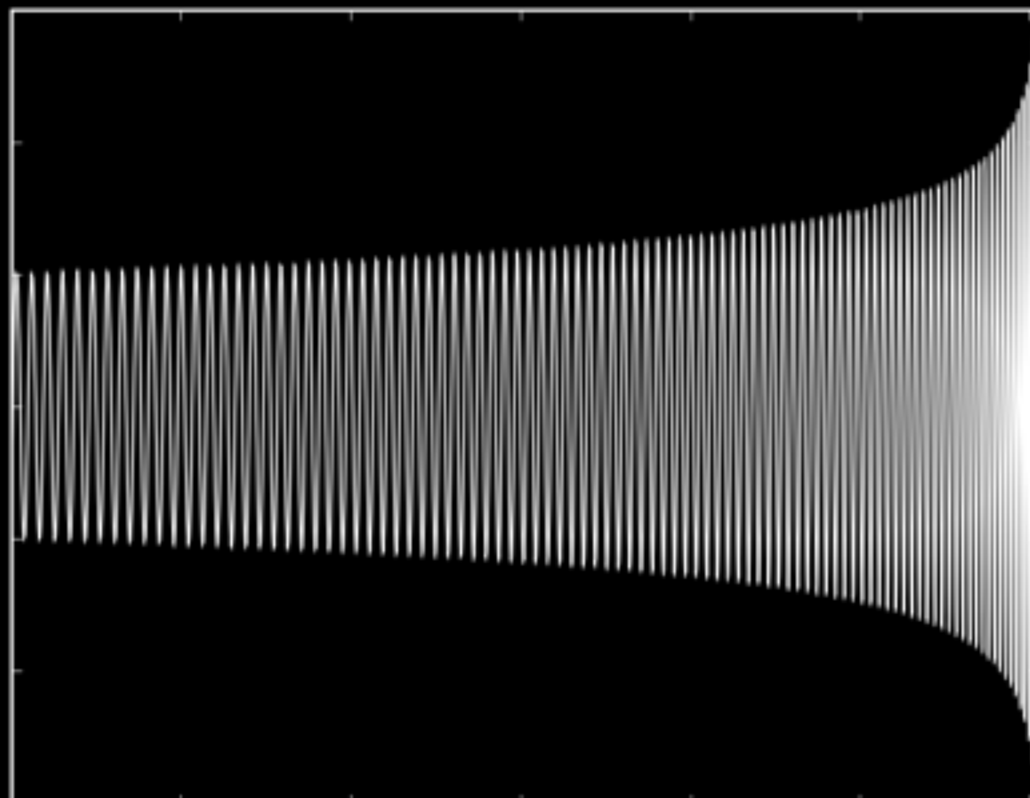
- Gravitational wave phasing depends on masses, spins, finite size effects...
- But to leading order just depends on the "chirp mass"

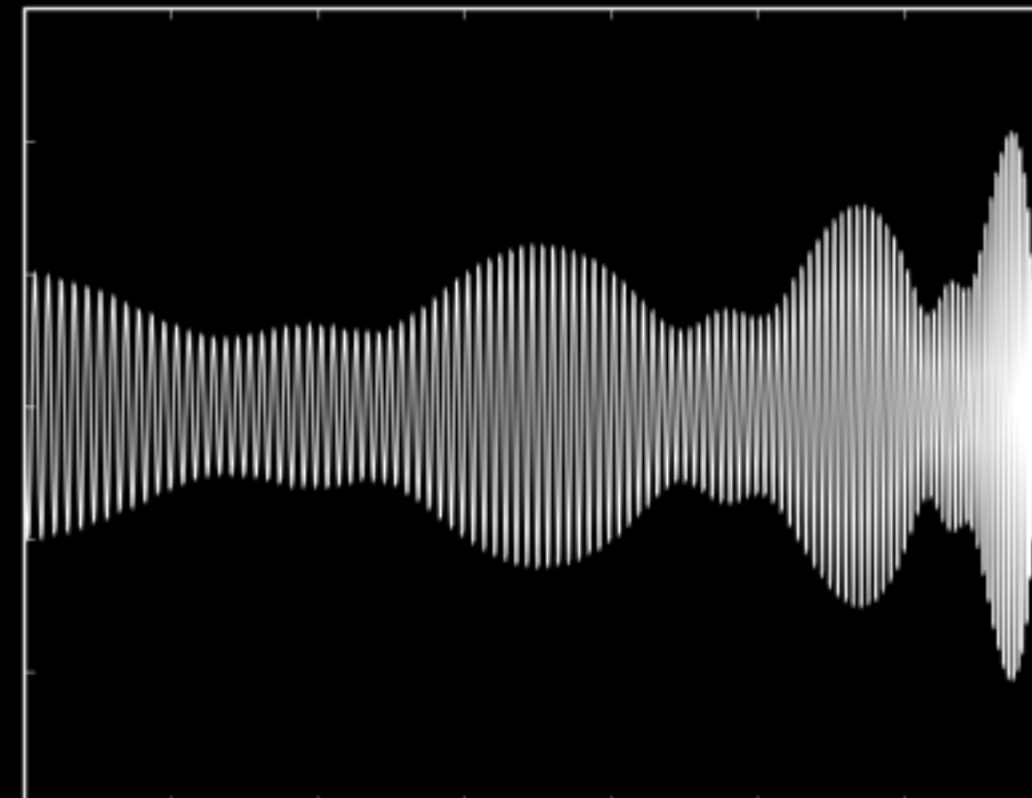
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

- Other parameters can be degenerate or hard to measure

Non-spinning

Spinning





$h(t)$

t

t

$$(M = m_1 + m_2, \\ \eta = m_1 m_2 / M^2)$$

$$(M, \eta, \vec{s}_1, \vec{s}_2, \hat{L}_N, \alpha, \delta, \ldots)$$

Apostolatos, Cutler, Susssman, Thorne PRD **49** 6274 (1994)

Apostolatos PRD **52** 605 (1995)

Kidder PRD **52** 821 (1995)

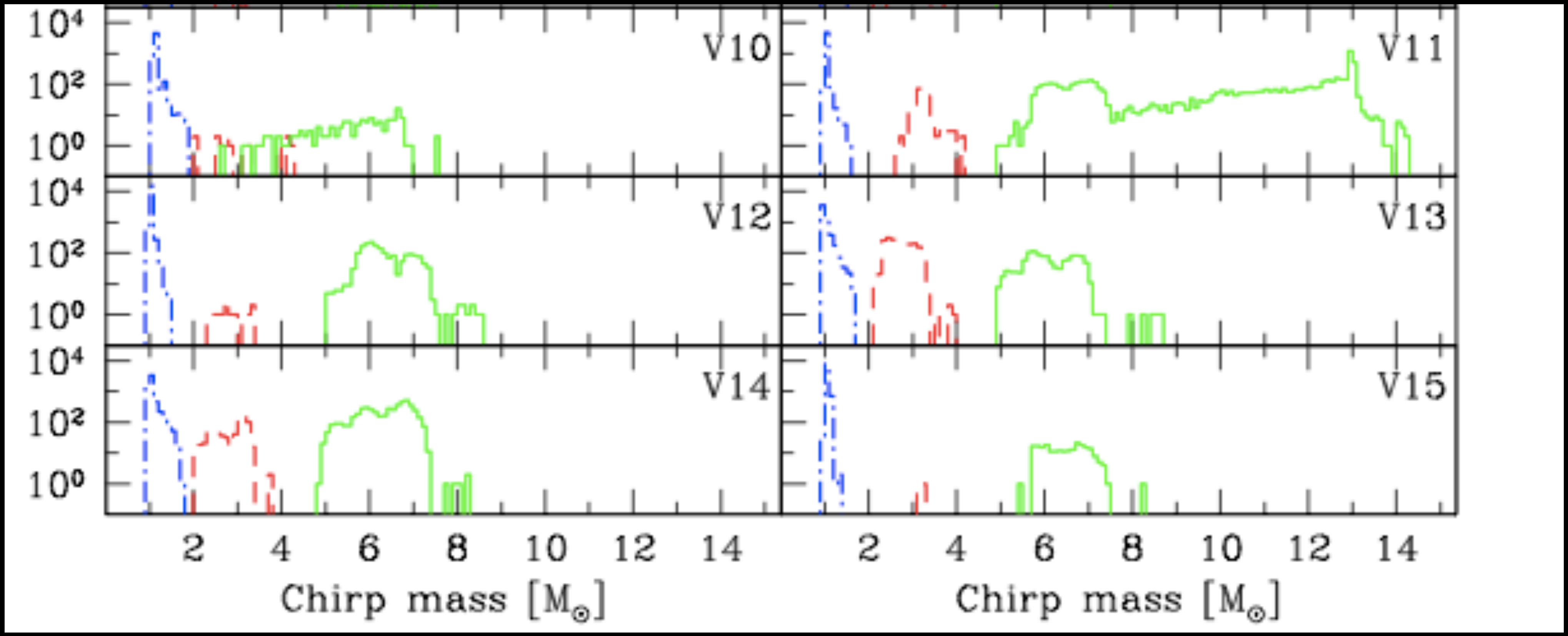
Buonanno, Chen, Vallisneri PRD **67** 104025 (2003)

Pan, Buonanno, Chen, Valisneri PRD **69** 104017 (2004)

DAB, Lundgren, O'Shaugnessy PRD **86** 064020 (2012)

- Can we probe the "mass gap" between neutron stars and black holes?

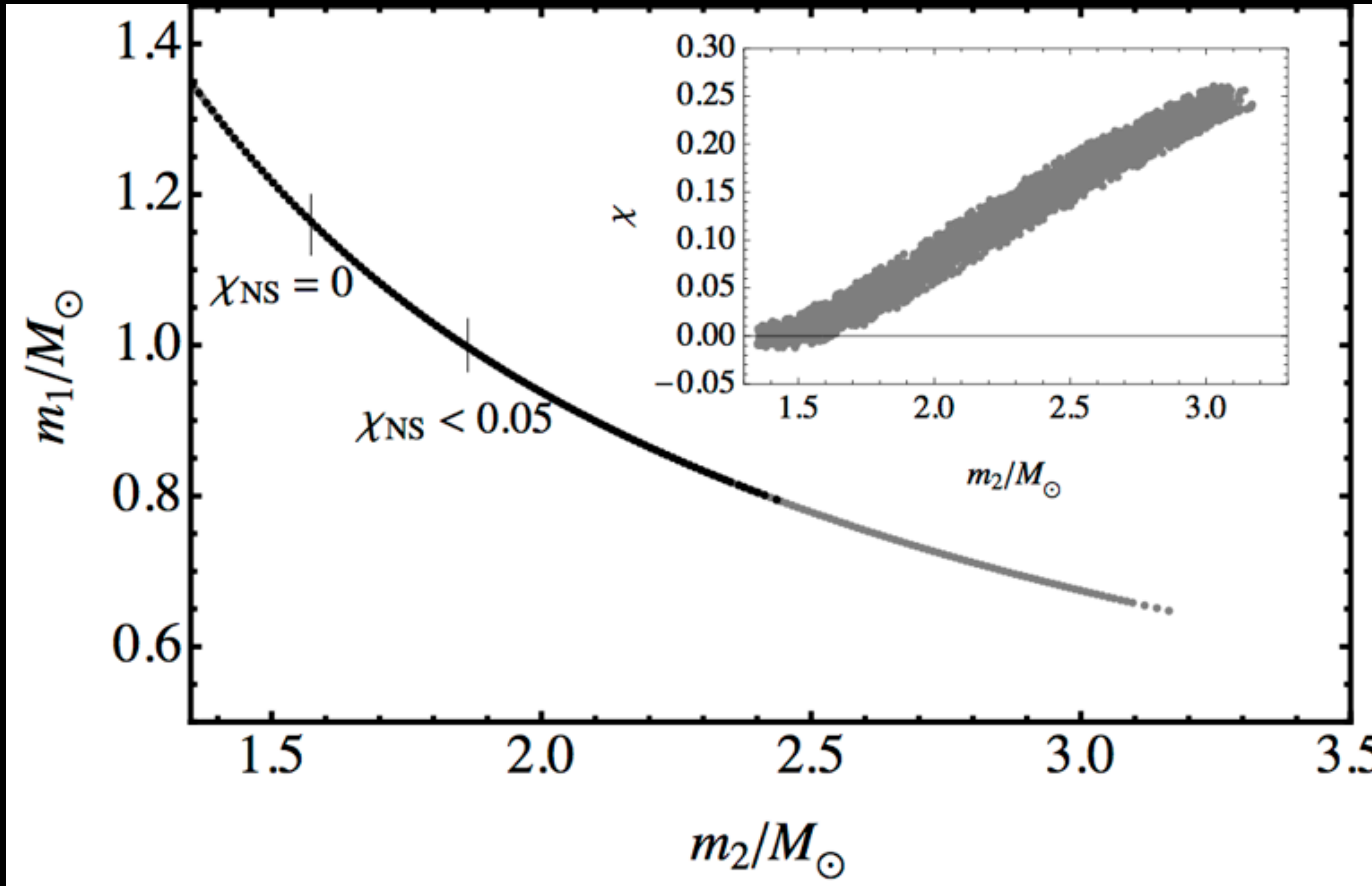
- Can high mass black hole detection probe the initial mass function and common envelope?



Dominik, et al. ApJ **52** 759 (2012)

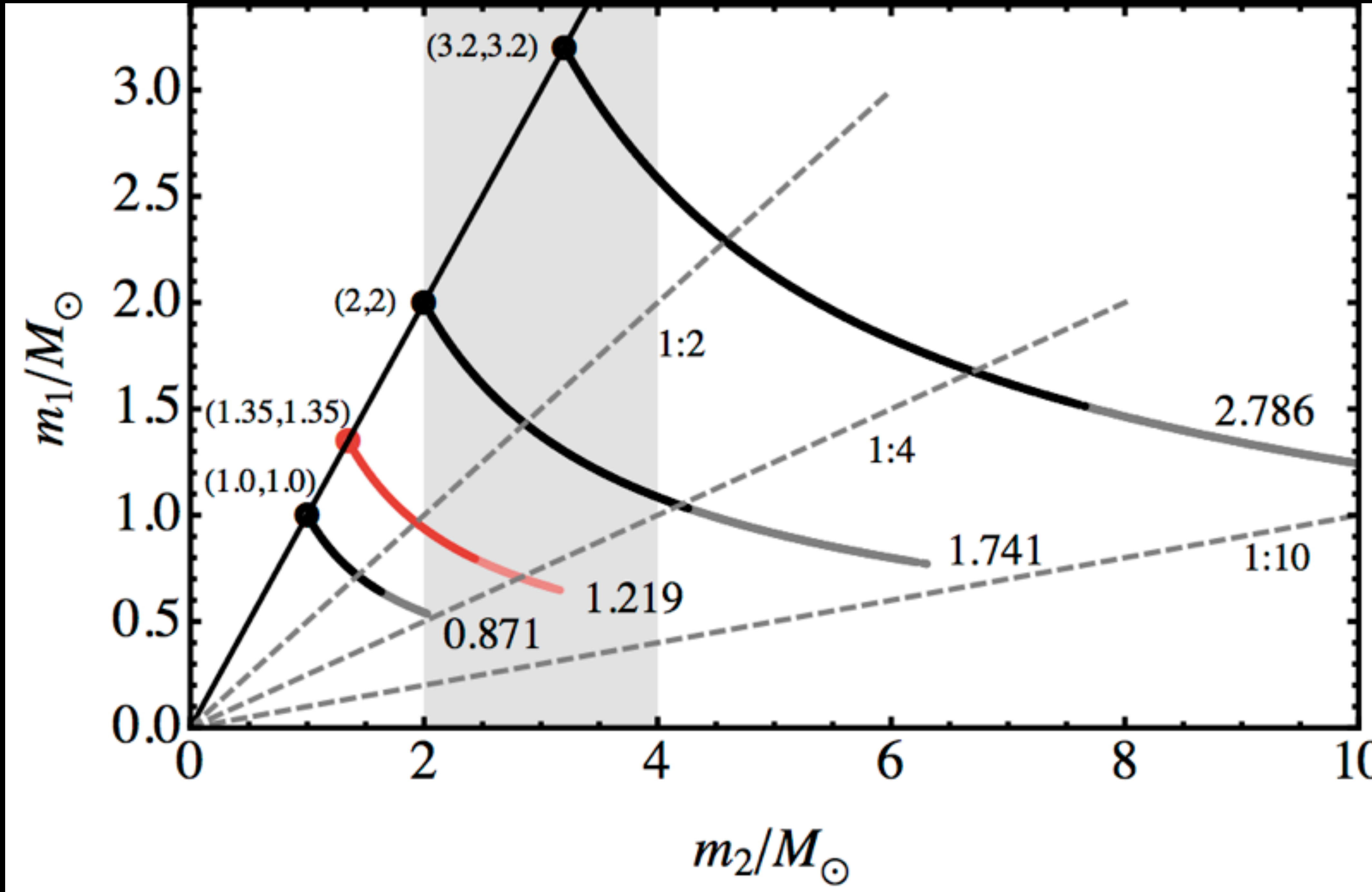
- We know that we measure the chirp mass most accurately (~0.01% for BNS) and symmetric mass ratio less accurately (~1.3% for non-spinning BNS systems)

- Spin and mass ratio can be degenerate in the phase evolution and this can impact our ability to measure the mass ratio:



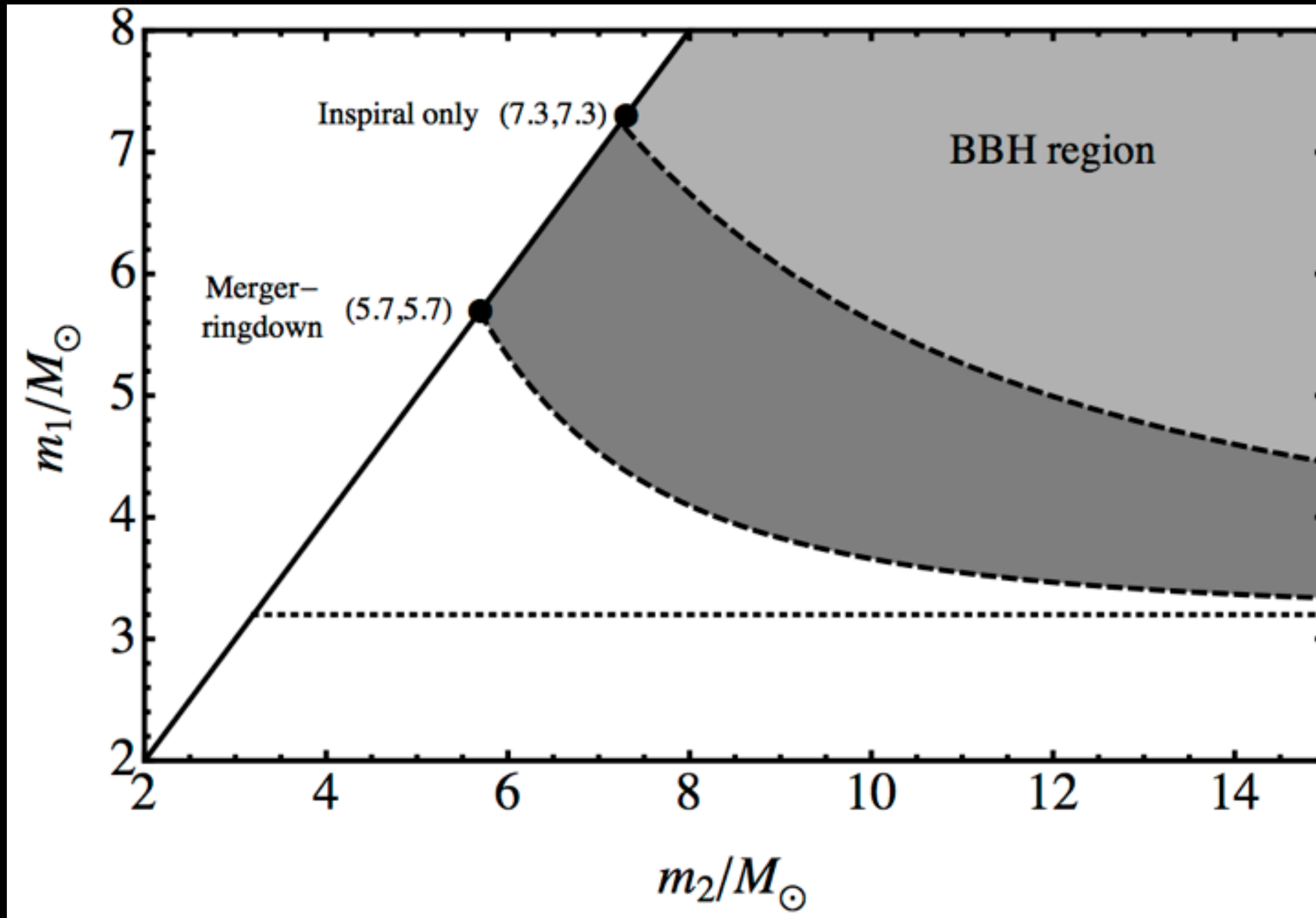
- (1.35,1.35) M_{sun} BNS signal
- What systems could be degenerate with this?

Hannam, DAB, Fairhurst, Fryer, Harry Astrophys J Letters 766 L14 (2013)



- There is a degeneracy between BNS, NSBH, and BBH

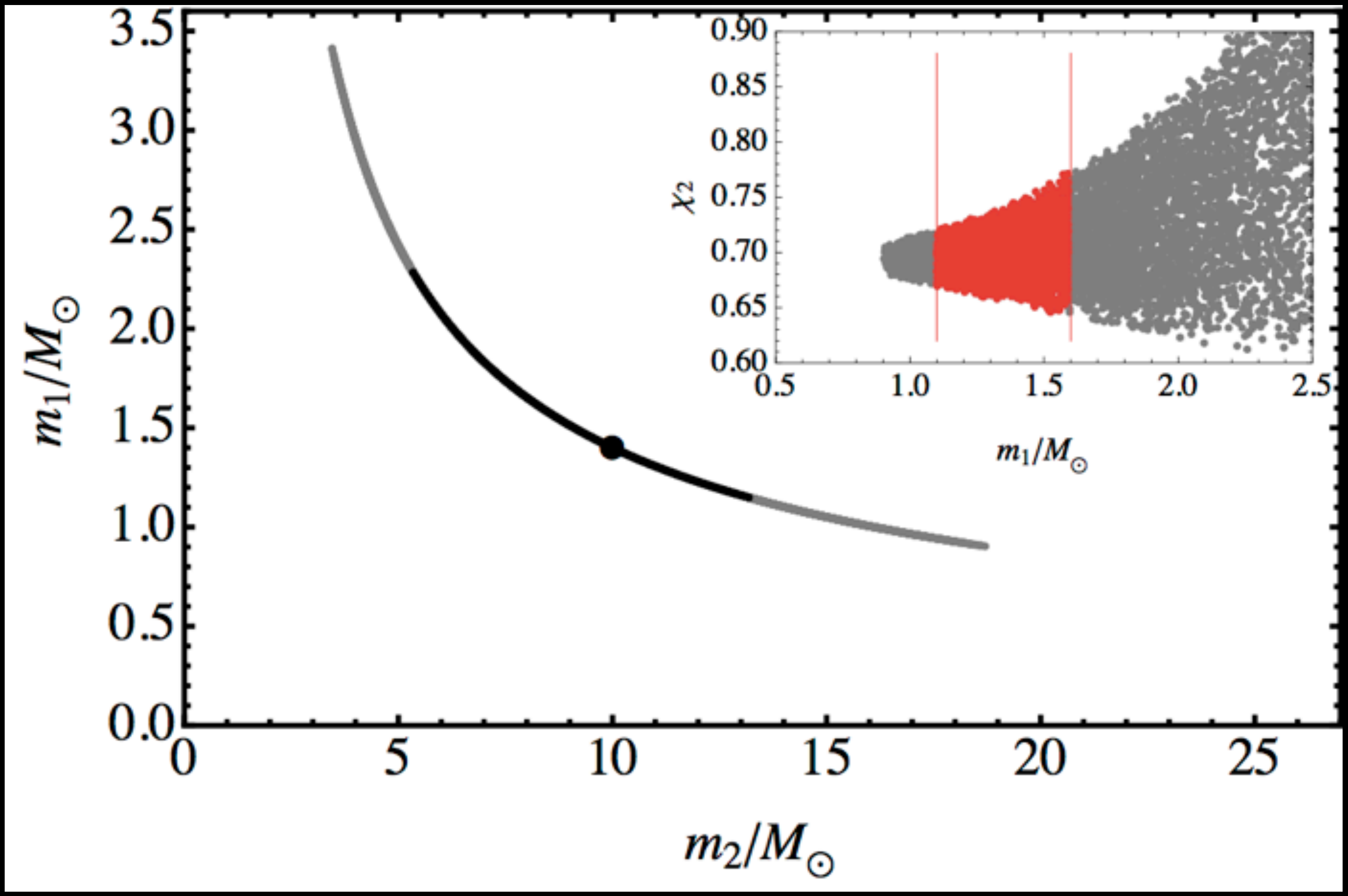
Hannam, DAB, Fairhurst, Fryer, Harry Astrophys J Letters 766 L14 (2013)



- Merger-ringdown can help break the NSBH/BBH degeneracy, but we need an accurate waveform to do this

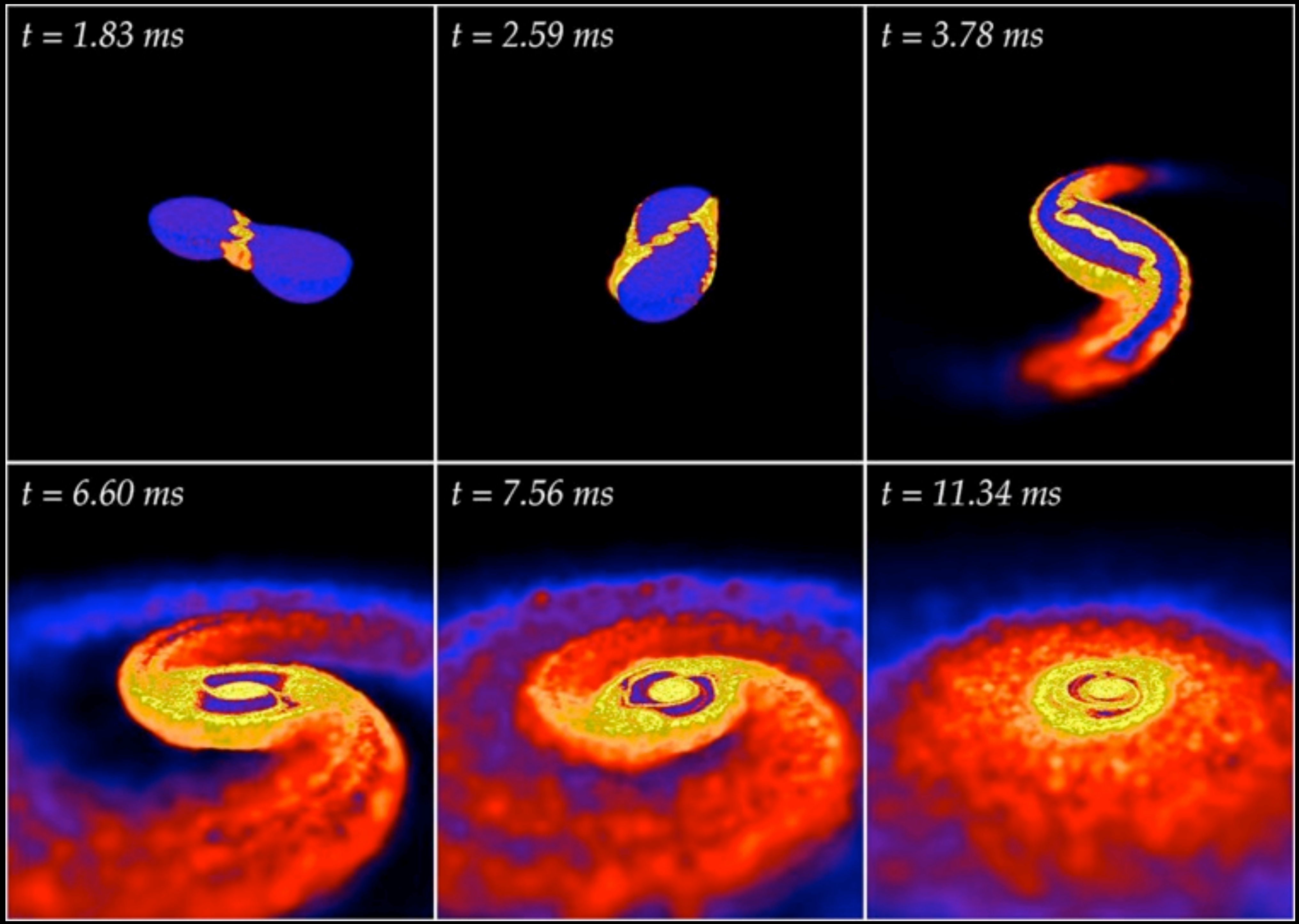
Hannam, DAB, Fairhurst, Fryer, Harry Astrophys J Letters 766 L14 (2013)

- Observing an EM counterpart (GRB, orphan afterglow, kilonovae) would help break degeneracy



Hannam, DAB, Fairhurst, Fryer, Harry Astrophys J Letters 766 L14 (2013)

Kilonova: neutron rich matter ejected in tidal tails and disk wind leads to EM emission

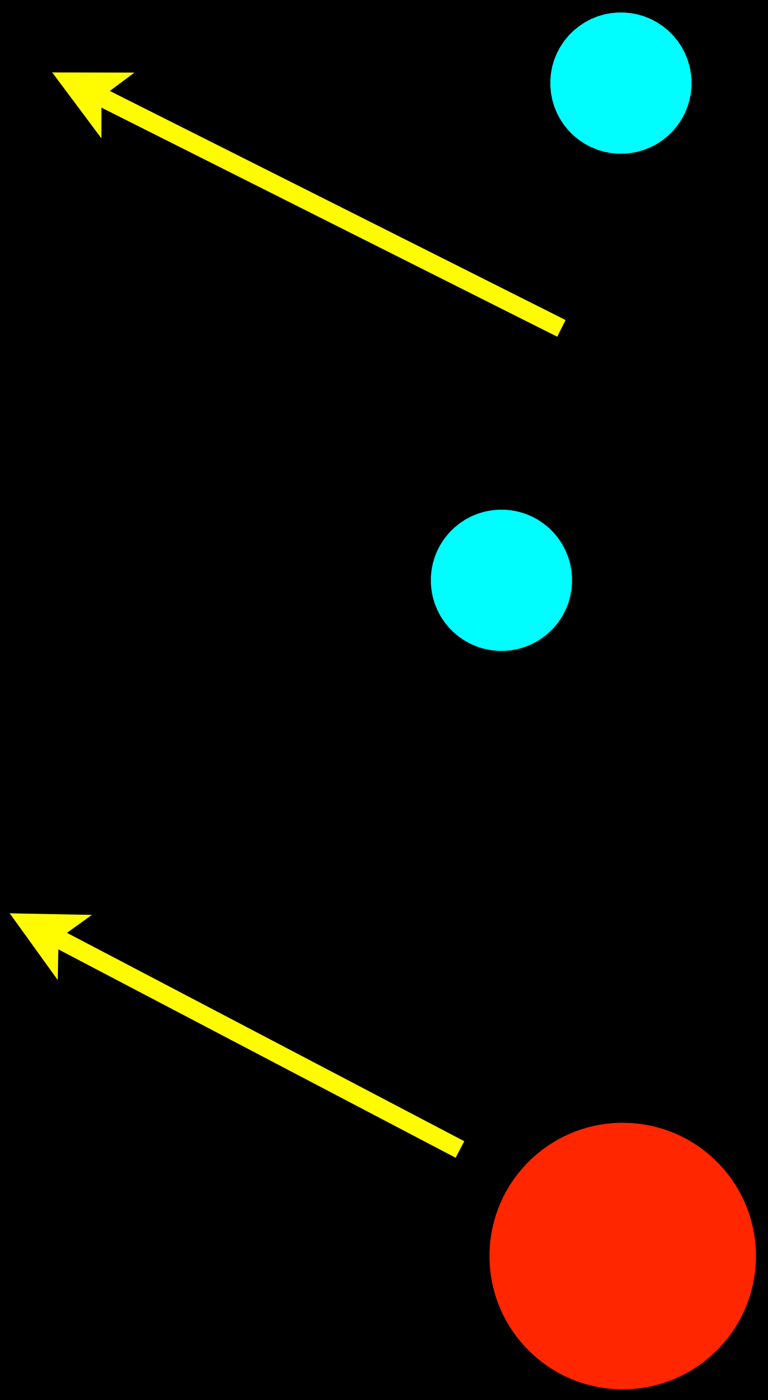


Li and Paczynski (1998); Kulkarni (2005); Rosswog (2005); Metzger et al. (2010)

- GWs come directly from bulk motion of the source

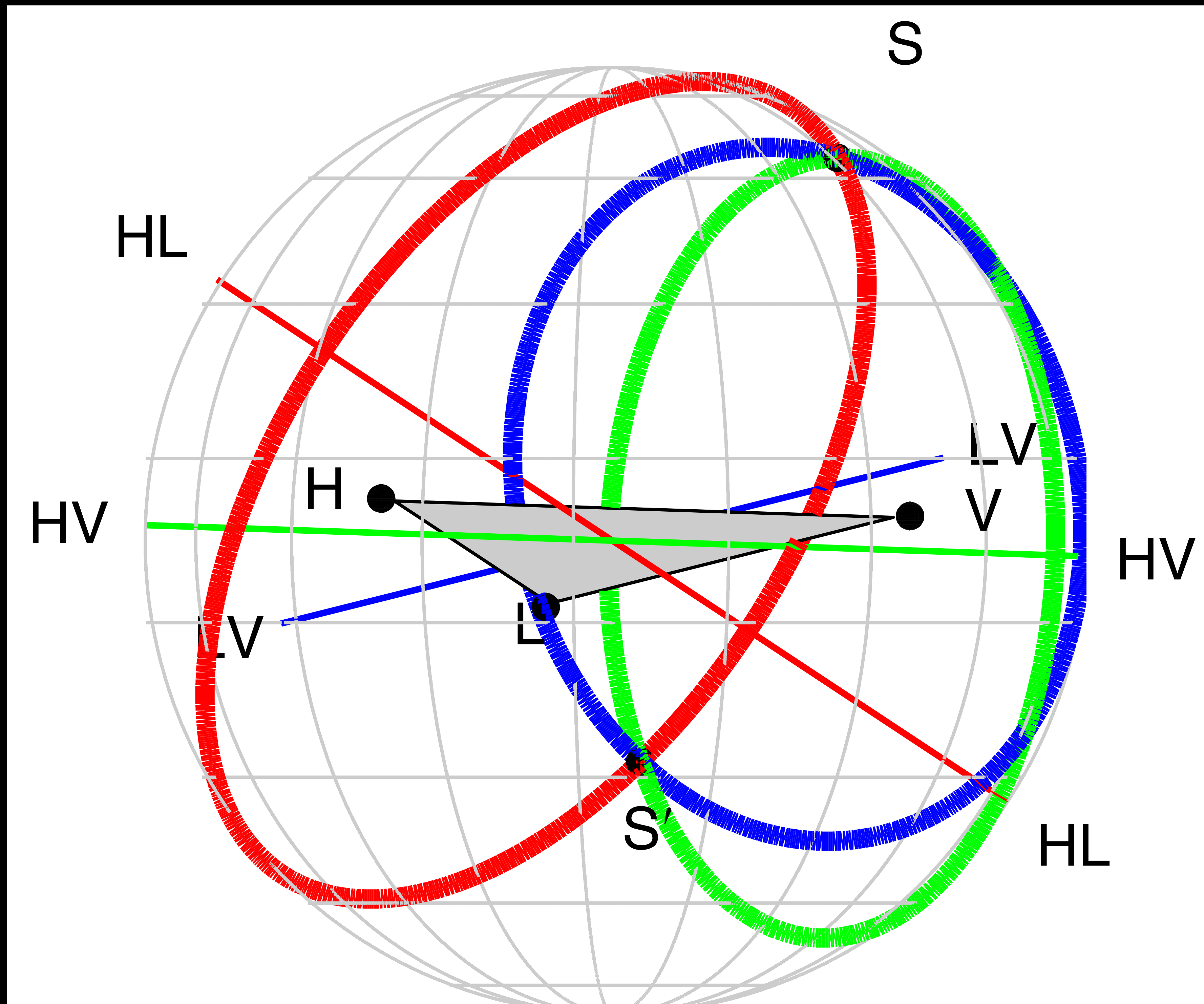
- EM emission is highly reprocessed

- Lots of complementary information for us to extract from observations



Joint EM-GW observations will give us the host galaxy, association with stellar population, accurate distance, merger hydrodynamics, jet formation, etc.

Source Localization with a network

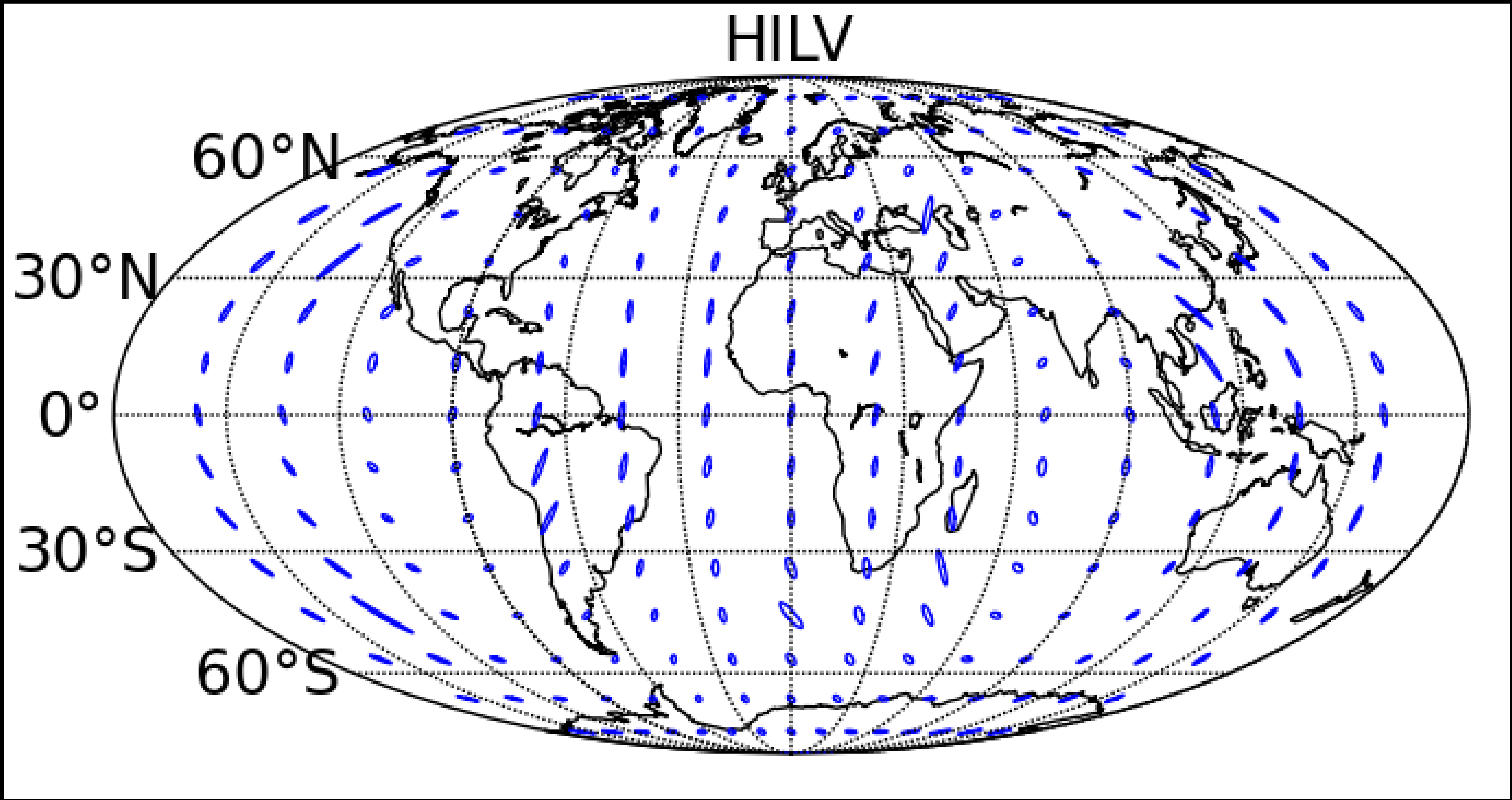


Chatterji et al. Phys Rev D **74** 0802005 (2006), Fairhurst New J.Phys. **11** 123006 (2009)

	Number of BNS detections	Localized to 5 deg sq	Localized to 20 deg sq
2015	0.0004 - 3	-	-
2016-7	0.006 - 20	2%	5 - 12%
2017-8	0.04 - 100	1 - 2%	10 - 12%
2019	0.4 - 400	3 - 8 %	8 - 28 %

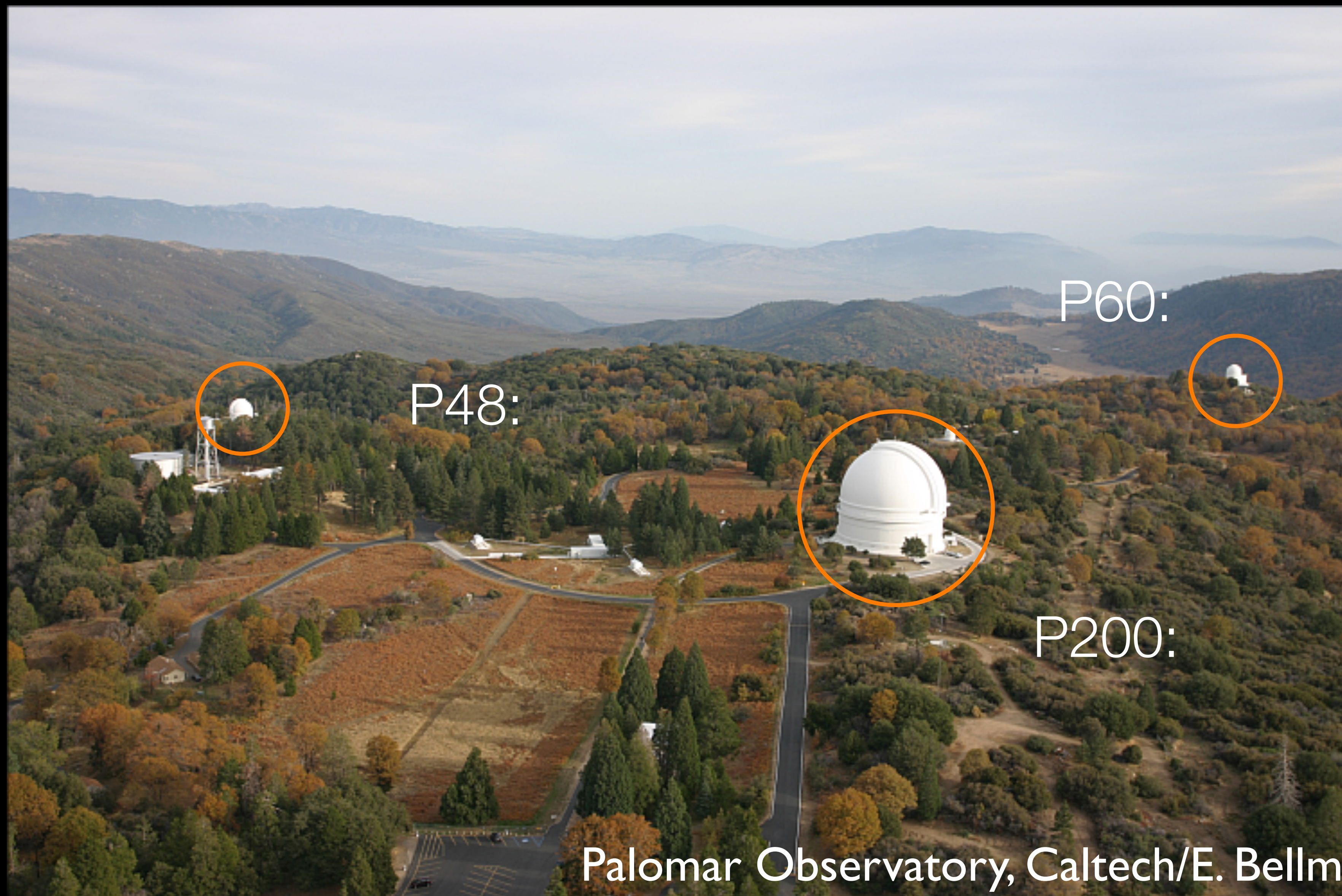
Aasi, ..., DAB, et al. (LSC and Virgo) arXiv:1304.0607

LIGO India: 17% (48%) of sources located to 5 (20) deg sq



Aasi, ..., DAB, et al. (LSC and Virgo) arXiv:1304.0607

Palomar Transient Factory

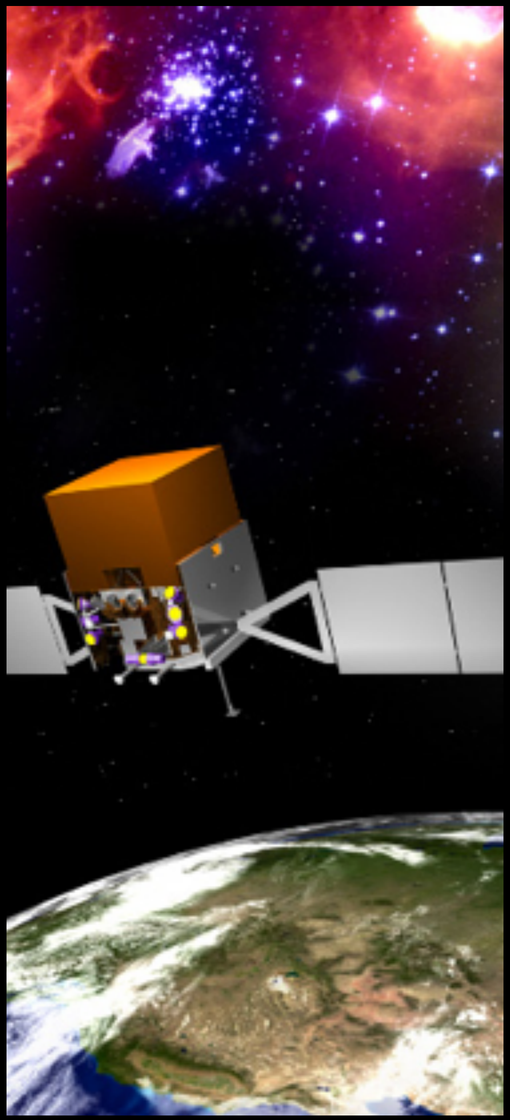


P48 Survey telescope (≈7 deg^2 FOV, R≈20.6 mag in 60 s)

P60 Robotic, photometric follow-up

P200 Spectroscopy, classificatioN

Fermi Gamma Ray Bursts

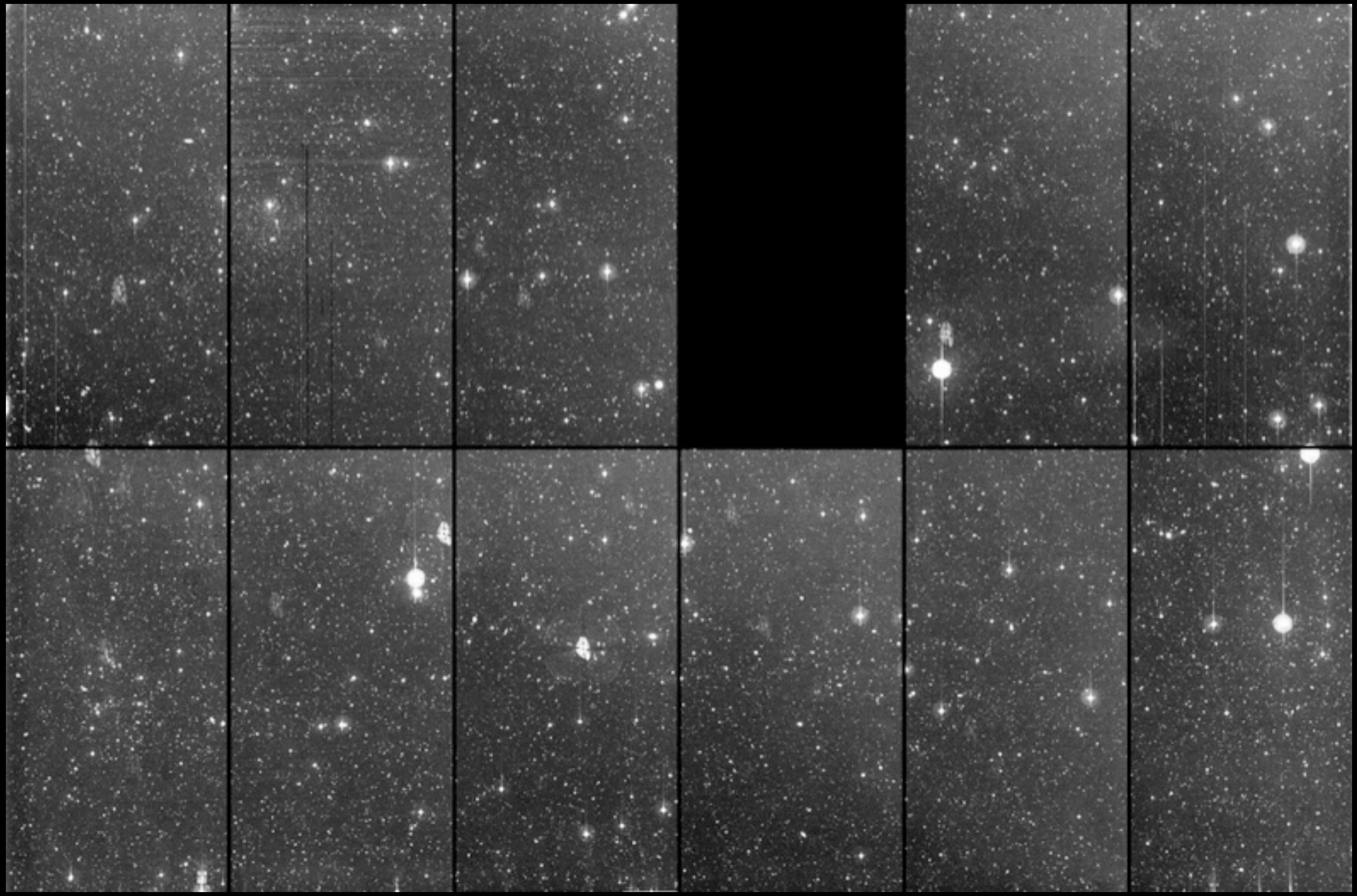


NASA/GSFC

Fermi GBM has twice the detection rate of Swift BAT

70% of sky and better for short GRBs

But very coarse localization, so very hard to follow up and observe afterglows



P48 has ~ 7 square degree field of view

Tile the Fermi error box and follow up GBM GRBs

Fermi trigger on July 2, 2013

27,004 transient/variable candidates found by real-time iPTF analysis

26,960 not known minor planets

2740 sources without SDSS detections brighter than r'=21

43 sources detected in both P48 visits, presented to human scanners

7 sources saved by humans

3 afterglow-like candidates scheduled for follow-up

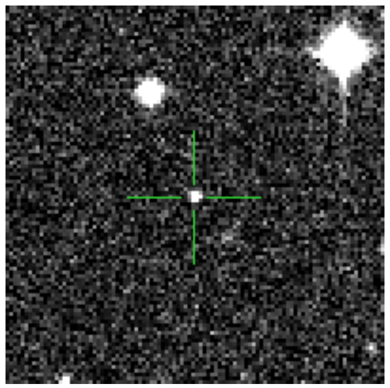
13bxj SN II

14:20:59.41 +15:09:42.1
215.247521 +15.161706

View another

OVERVIEW PHOTOMETRY SPECTROSCOPY FOLLOWUP OBSERVABILITY FINDING CHART EXAMINE PAGE

NEW



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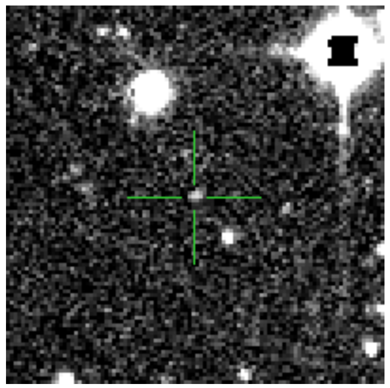
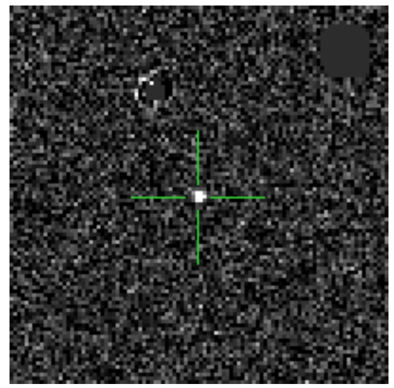
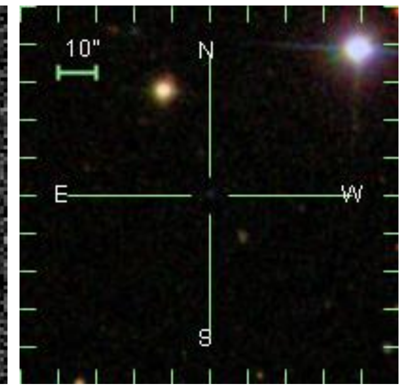
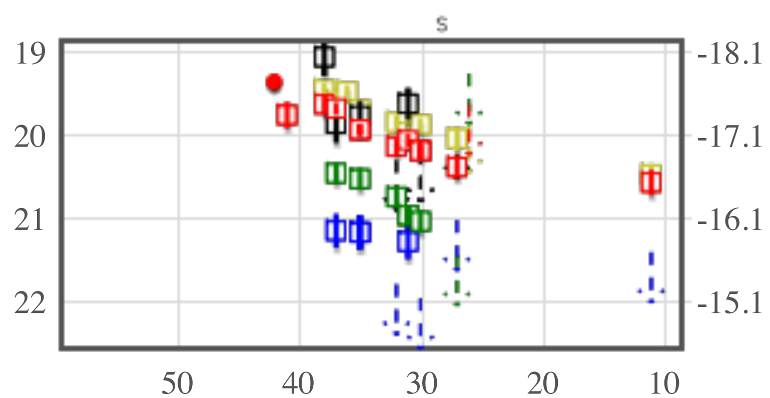


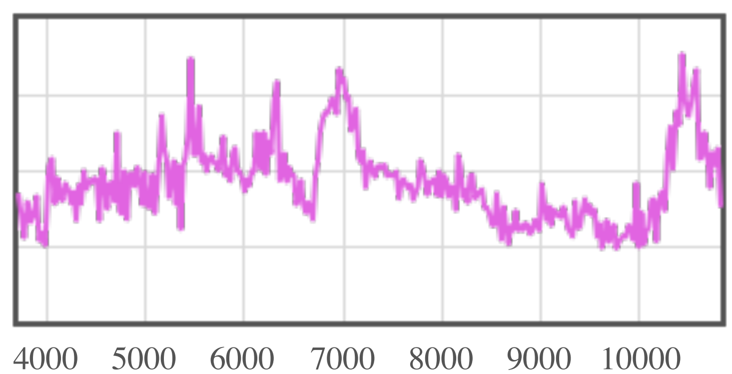
SUB



SDSS







r = 19.4 (42.2 d) | Upload New Photometry

z = 0.06 | Upload New Spectroscopy
DM (approximate) = 37.11

COMMENTS

2013 Jul 16 sagi [redshift]: 0.06
2013 Jul 16 sagi [classification]: SN II
2013 Jul 16 sagi [phase]: +7 days
2013 Jul 16 sagi [comment]: SSF best match is to SN 1987K at +7 days [view attachment]
2013 Jul 15 iair [info]: Observed at P200+DBSP
2013 Jul 02 duncan [info]: Observation triggered by Fermi/GBM trigger Fermi394416326
2013 Jul 02 ofer [info]: Faint host. No limits.
2013 Jul 02 ofer [type]: Transient

Add a Comment:

Attach File: Choose File no file selected

info Save Comment

ADDITIONAL INFO

NED | SIMBAD | VizieR | HEASARC | SkyView | PyMP | Extinction

IPAC | DSS | WISE | Subaru | VLT | Variable Marshal (Search) | ADS

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FOLLOW UP

PROGRAMS

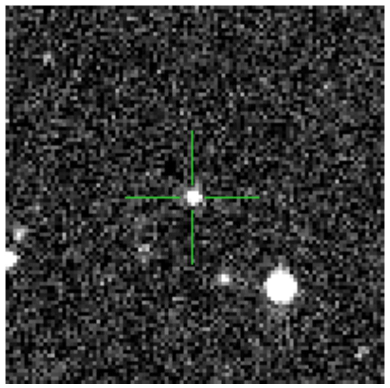
13bxk AGN

14:27:42.19 +16:02:55.5
216.925803 +16.048758

View another

OVERVIEW | PHOTOMETRY | SPECTROSCOPY | FOLLOWUP | OBSERVABILITY | FINDING CHART | EXAMINE PAGE

NEW



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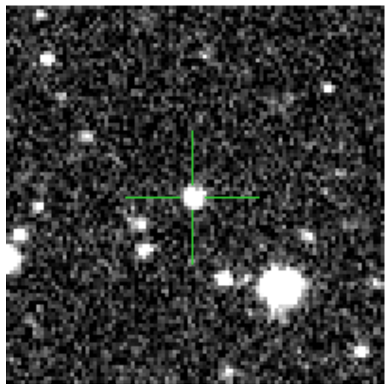
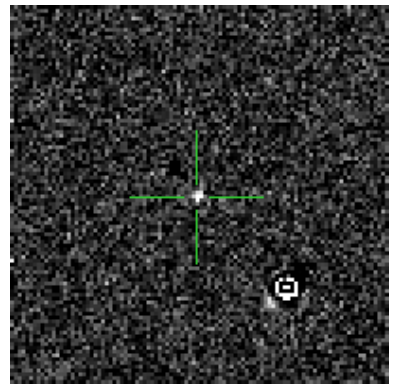
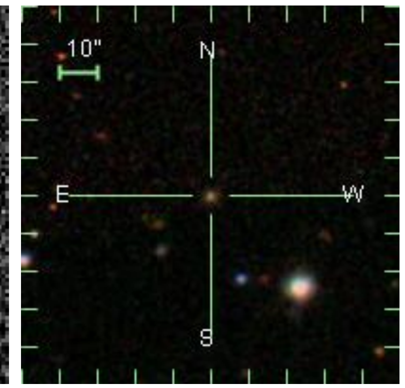
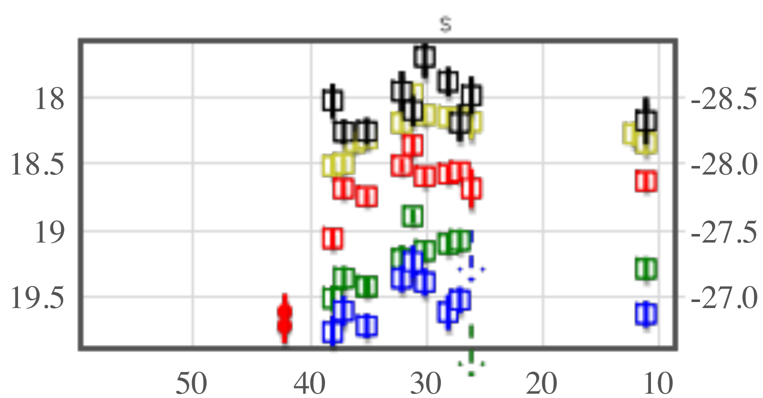


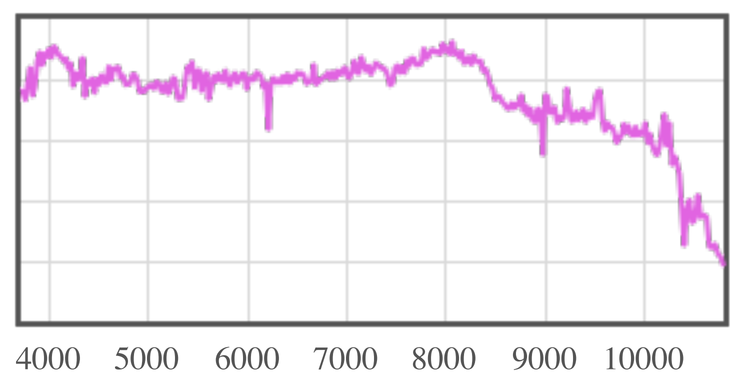
SUB



SDSS







r = 19.6 (42.2 d) | Upload New Photometry

z = 2.405 | Upload New Spectroscopy
DM (approximate) = 46.47

ADDITIONAL INFO

NED | SIMBAD | VizieR | HEASARC | SkyView | PyMP | Extinction
IPAC | DSS | WISE | Subaru | VLT | Variable Marshal (Search) | ADS

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FOLLOW UP

PROGRAMS

COMMENTS

2013 Jul 16 avishay [comment]: Resolved Mg II 2800A + weak CIV 1549
2013 Jul 16 sagi [classification]: AGN
2013 Jul 16 sagi [info]: Quasar
2013 Jul 16 sagi [redshift]: 2.405
2013 Jul 15 iair [info]: Observed at P200+DBSP
2013 Jul 02 duncan [info]: Observation triggered by Fermi/GBM trigger Fermi394416326
2013 Jul 02 ofer [info]: Dwarf/far-away host. No previous photometry.
2013 Jul 02 ofer [type]: Transient

Add a Comment:

Attach File: Choose File no file selected

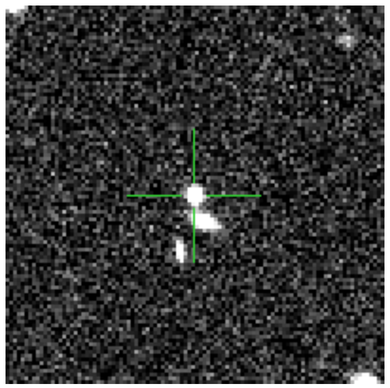
info | Save Comment

13bxl

14:29:14.78 +15:46:26.4
217.311582 +15.774013

View another

NEW



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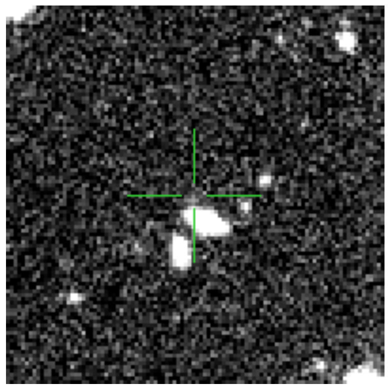
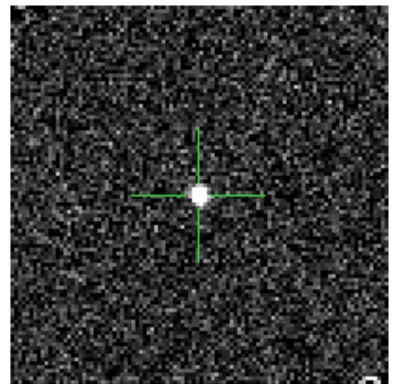
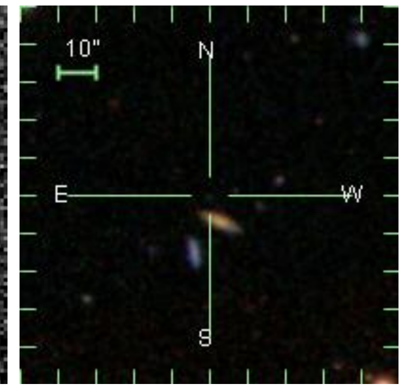
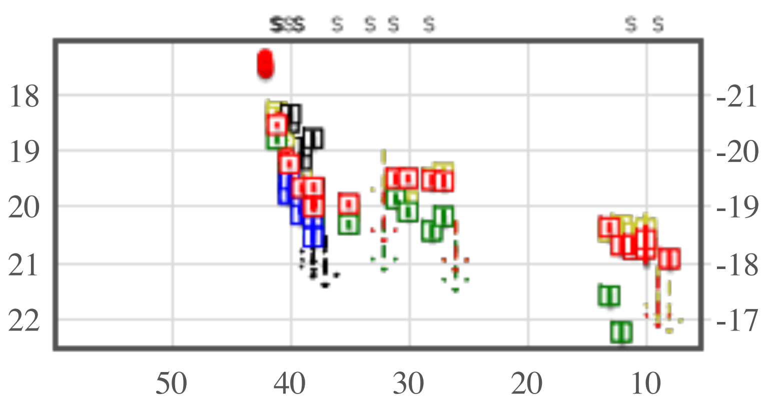


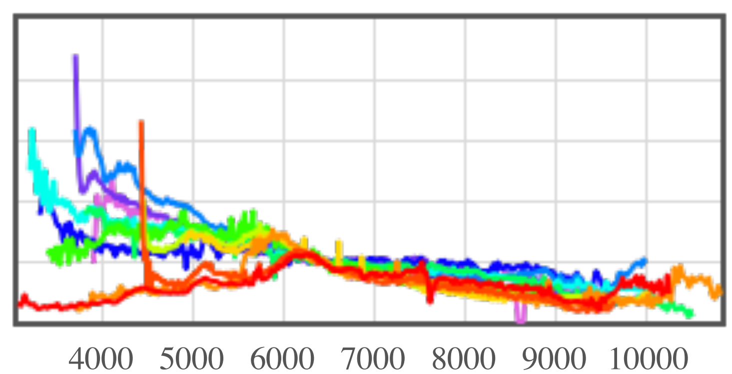
SUB



SDSS







r = 17.6 (42.2 d) | Upload New Photometry

z = 0.145 | Upload New Spectroscopy
DM (approximate) = 39.19

ADDITIONAL INFO

NED	SIMBAD	VizieR	HEASARC	SkyView	PyMP	Extinction
IPAC	DSS	WISE	Subaru	VLT	Variable Marshal (Search)	ADS

Add to Cart

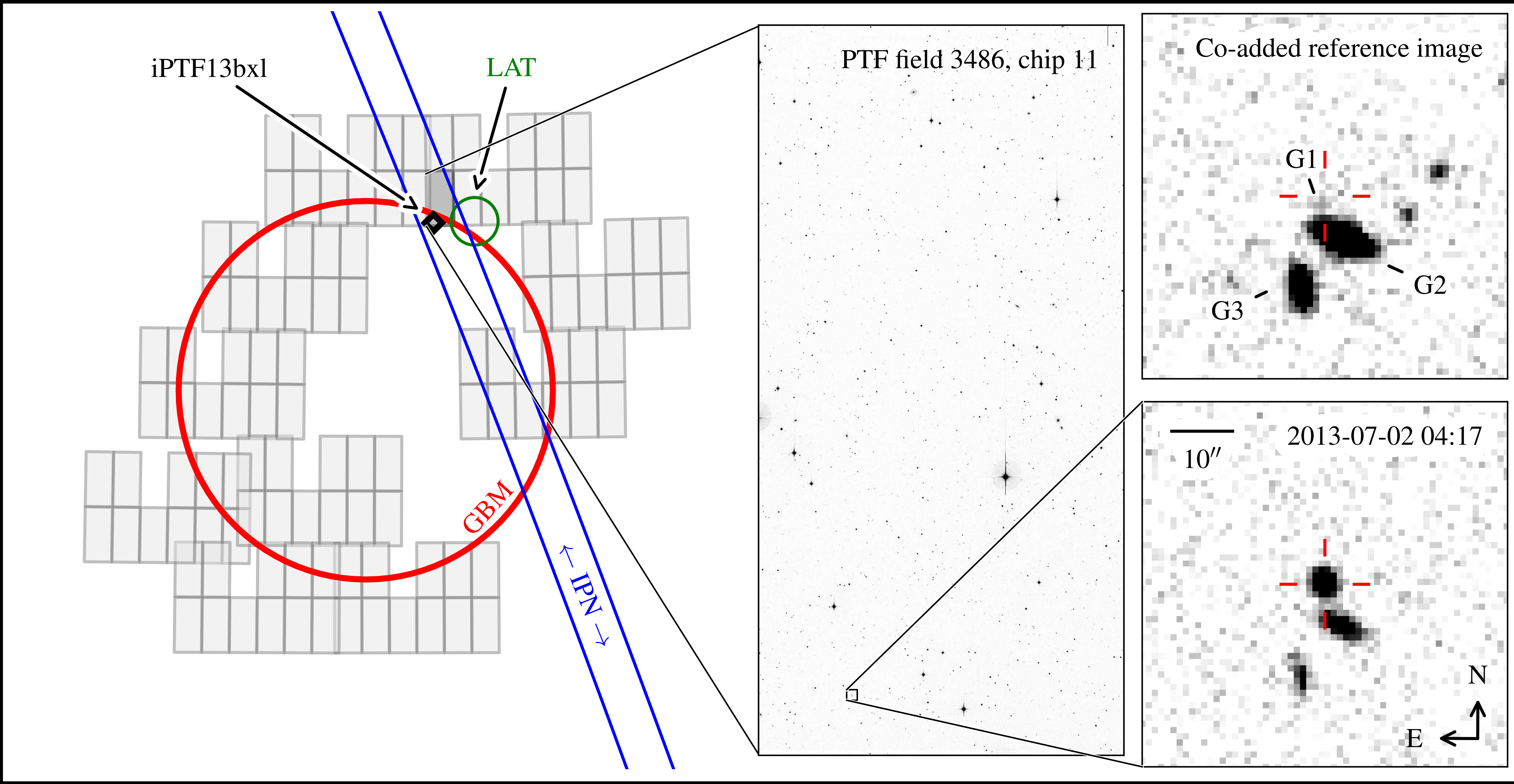
FOLLOW UP

PROGRAMS

COMMENTS

2013 Aug 04 sumin [info]: observed with LRIS
2013 Jul 15 iair [info]: Observed at P200+DBSP (PA 166.1)
2013 Jul 14 jesper [info]: Latest Keck spectrum (July 11) looks like 2006aj close to Max. The fit with 98bw is less good.
2013 Jul 11 sumin [info]: observed with lick 3-m kast, g-band and R-band images
2013 Jul 11 sumin [info]: observed with Lick Kast g-band image, 130711
2013 Jul 09 brad [info]: Broad features identified in NOT spectrum (GCN 14994) are clearly visible. But it doesn't look like an exact match to 98bw to me (see attached). [view attachment]
2013 Jul 08 robert [info]: Light curve is still fading as a powerlaw (see attached plot). Could have been a break in the LC before 10^5 seconds. [view attachment]
2013 Jul 06 jesper [info]: interesting features, and about right timing. Although some structure also in earlier spectra. SNID attached. /jesper [view attachment]
2013 Jul 06 avishay [info]: SN signatures seem to be already emerging, as light curve decline slows down. Comparison with SN 1998bw and SN 2006aj attached. [view attachment]
2013 Jul 05 ofer [comment]: Quick reduction (to be compared with final one)
2013 Jul 04 mansi [redshift]: 0.145
2013 Jul 04 iair [info]: Observed with P200+DBSP
2013 Jul 03 iair [redshift]: 0.145
2013 Jul 03 iair [comment]: possible redshift based on narrow H, O I, O III
2013 Jul 03 eric [info]: Observed with P200-DBSP 130703
2013 Jul 03 duncan [info]: There is a Fermi/LAT detection (GRB130702A). The best LAT on-ground location is found to be: RA, DEC = 216.4, 15.8 (J2000), with an error radius of 0.5 deg (90% containment, statistical error only) This position is 4 deg from the best GBM position (RA, Dec = 218.81, +12.25 with a 4 deg radius), and 0.8 deg from the position of the optical afterglow.
2013 Jul 02 eric [info]: Observed with P200-DBSP 130702
2013 Jul 02 duncan [info]: Final Fermi GBM position: +14h 35m 14s, +12d 15' 00" (218.810d, +12.250d) (J2000) Error 3.99 [deg radius, statistical only]

iPTF 13bxl: Discovery of Optical Counterpart in 71 deg sq



Singer, Cenko, Kasliwal, Perley, Ofek, DAB, et al. Astrophys J Letters **766** L34 (2013)

- The convergence of
  - Gravitational-wave experiments
  - Numerical and analytical relativity
  - Modeling of electromagnetic sources
  - Wide-field optical telescopes
- will give us the tools to revolutionize our astrophysical knowledge of the universe

What has LIGO seen so far?

Sensitivity Progress

Neutron star binaries visible in

Milky Way
(~ 50 kpc)

September 2002

Abbott, ..., DAB, et al. PRD **69** 122001 (2004)

Andromeda
(~700 kpc)

March 2003

Abbott, ..., DAB, et al. PRD **72** 082001(2005)

Virgo Cluster
(20+ Mpc)

September 2005+

Abbott, ..., DAB, et al. PRD **79** 122001 (2009)
Abbott, ..., DAB, et al. PRD **80** 047101(2009)
Abadie, ..., DAB, et al. PRD **82**102001 (2010)

- All LIGO and Virgo data up to October 20, 2010 has been searched for binary neutron stars and binary black holes

- No gravitational-wave candidates found

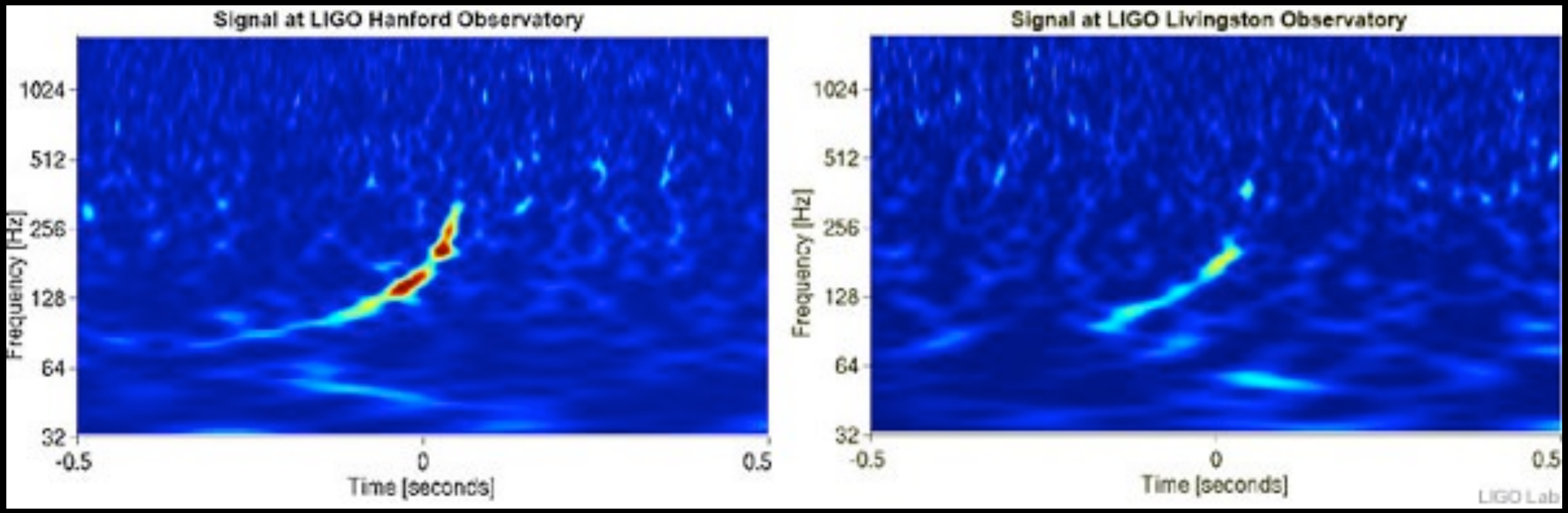
Abadie, ..., DAB, et al. PRD **85** 082002 (2012)
Aasi, ..., DAB, et al., PRD **87** 022002 (2013)

Blind Injection Challenge

- A loud candidate was found by the search
- False alarm rate was 1 in 7000 years
- A detection paper was written and approved for submission to Physical Review Letters
- Then we found out it was an injection...

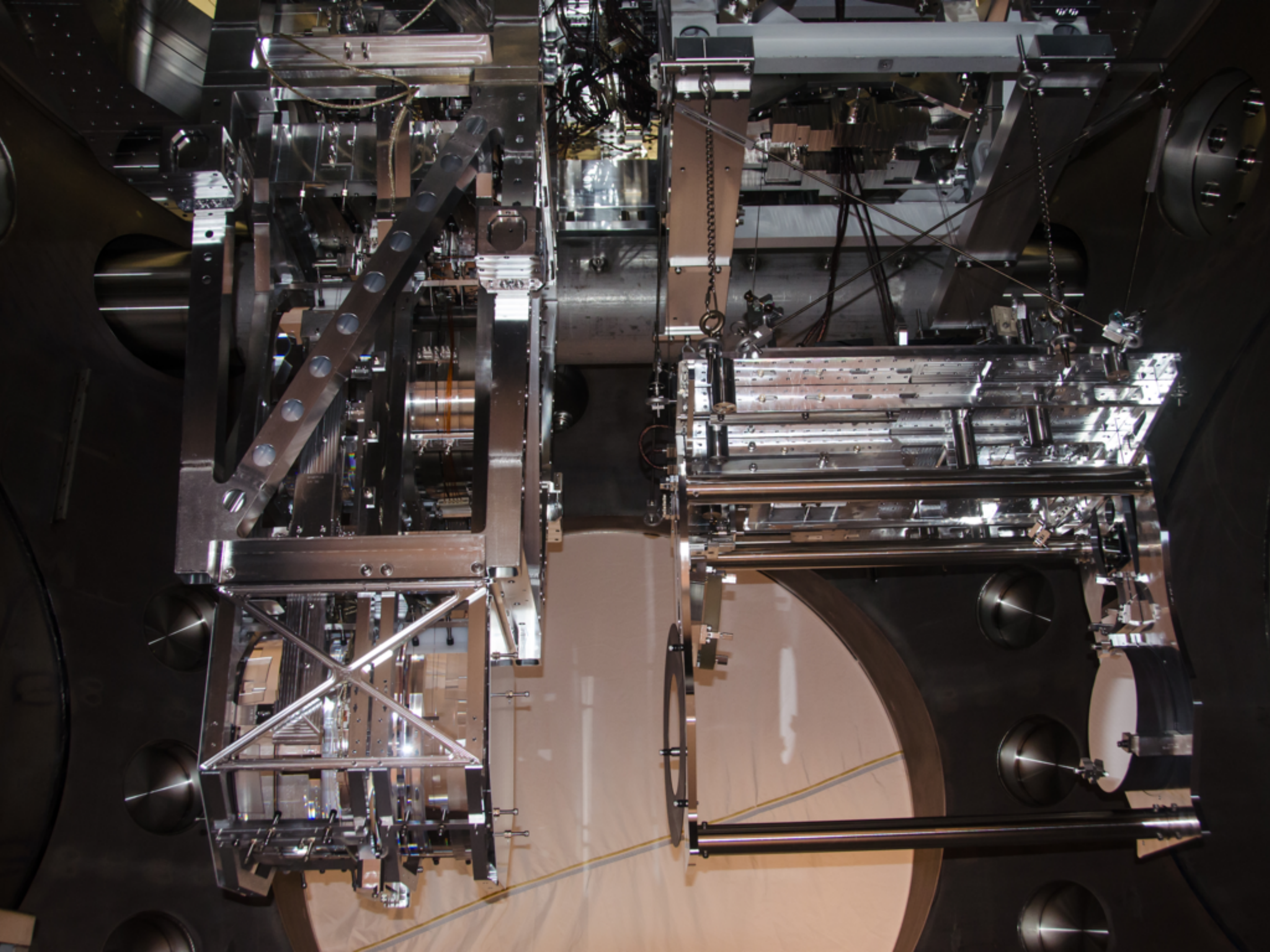
Blind Injection Challenge

- End-to-end test of detection capability in LSC-Virgo collaborations
- An inspiral signal was injected into the data without the knowledge: only three people in the collaboration knew

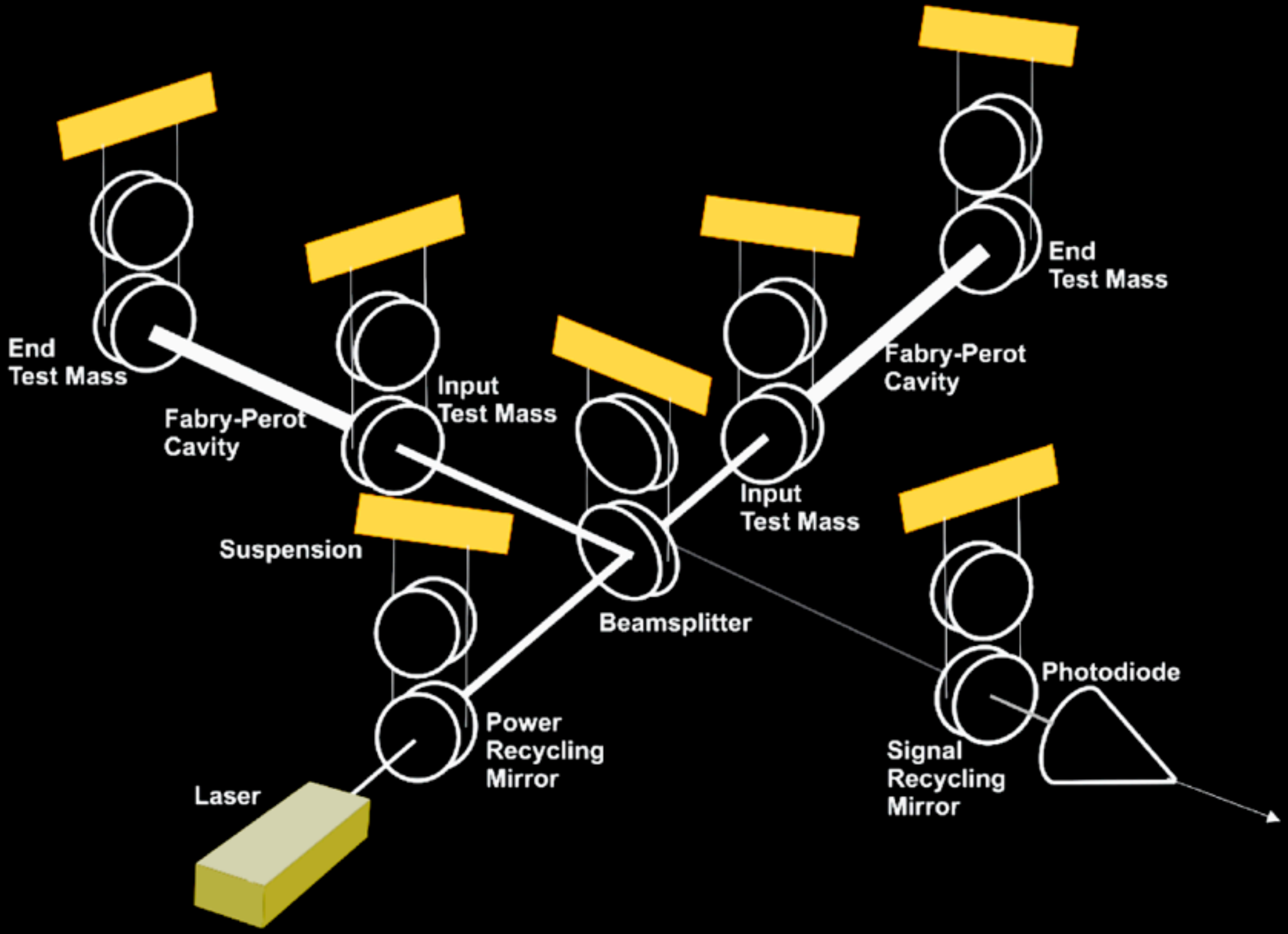


http://www.ligo.org/news/blind-injection.php

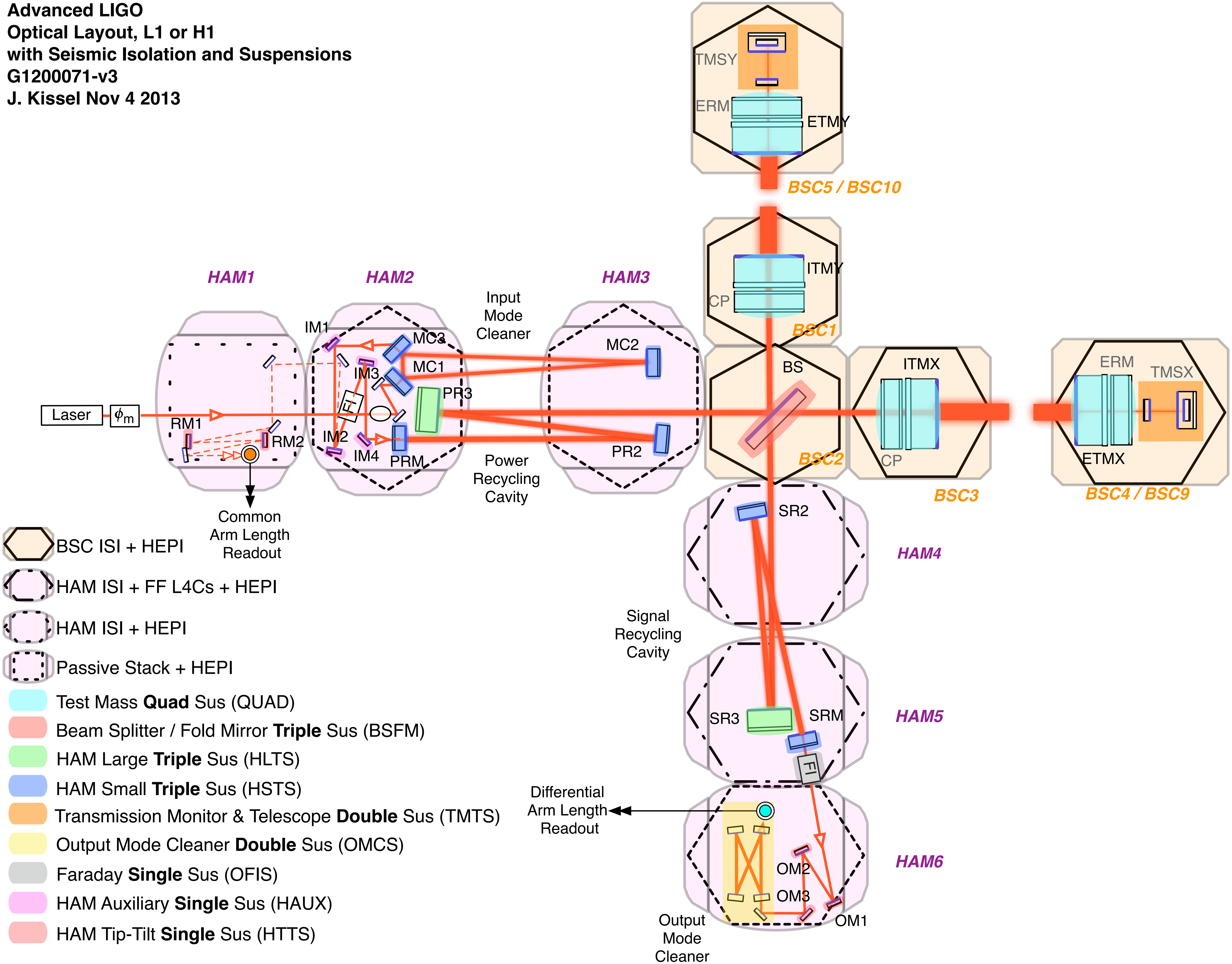
Where are we now?

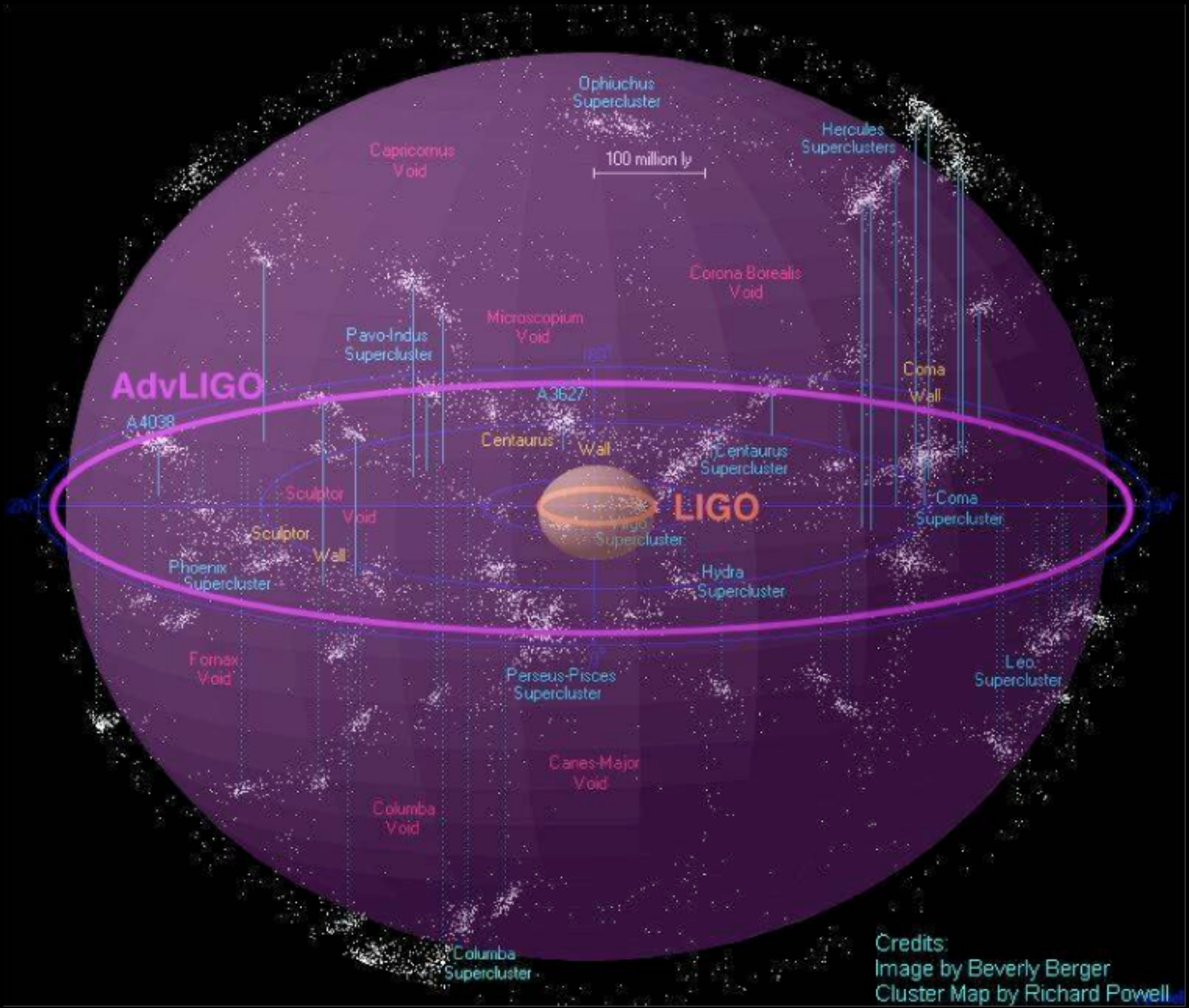


Advanced LIGO



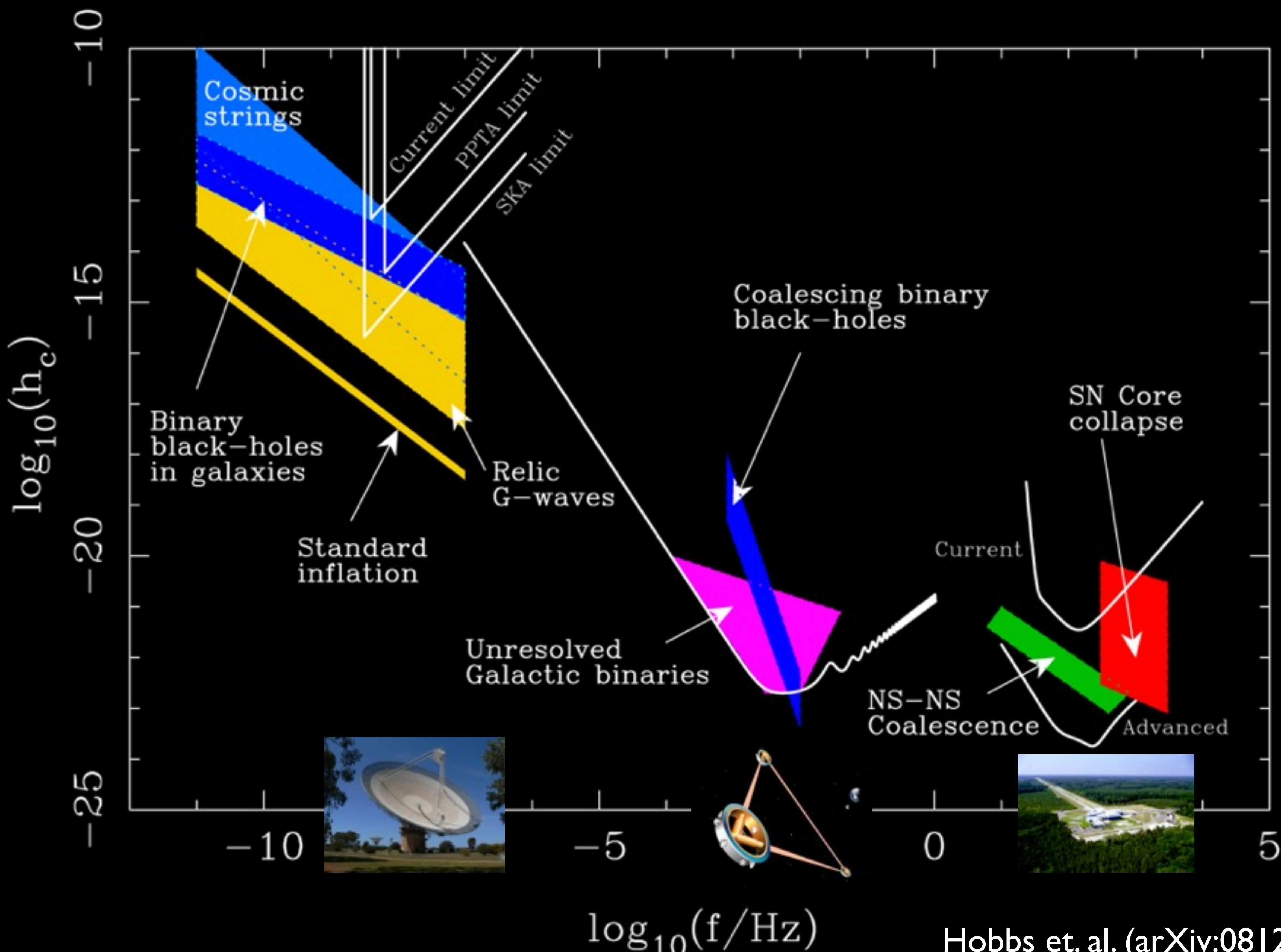
Advanced LIGO
Optical Layout, L1 or H1
with Seismic Isolation and Suspensions
G1200071-v3
J. Kissel Nov 4 2013





Ophiuchus Supercluster
Hercules Superclusters
Capricornus Void
100 million ly
Corona Borealis Void
Microscopium Void
Pavo-Indus Supercluster
AdvLIGO
A3627
Coma Wall
A4038
Centaurus
Wall
Centaurus Supercluster
Sculptor Void
LIGO
Virgo Supercluster
Coma Supercluster
Sculptor Wall
Phoenix Supercluster
Hydra Supercluster
Fornax Void
Perseus-Pisces Supercluster
Leo Supercluster
Canes Major Void
Columba Void
Columba Supercluster
Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

The Gravitational-Wave Spectrum



Hobbs et. al. (arXiv:0812.2721)


The future is bright for gravitational-wave astronomy